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TITLE: COMPACT-FAST RESPONSE ENVIRONMENTAL HEALTH MONITOR/TEMPERATURE SENSOR

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13. ABSTRACT *(Maximum 200 words)*

The objective of the Phase I effort was to determine the feasibility of developing a viable, hand-held environmental health monitor-a temperature sensing suite capable of supporting a heat-stress management computer model. Experimental findings indicate that the miniaturized black-globe thermometer, based upon digital integration of multiple surface thermosensors will indicate an equilibrium temperature value in approximately three minutes. The wet bulb with a miniaturized wetted surface will generate the natural wet bulb equilibrium temperature value in a similar time range. The dry bulb thermosensor to indicate the equilibrium temperature is a function of the thermistor rate constant. The integrated environmental health monitor concepts developed will rapidly provide the entire spectrum of environmental temperature parameters (wet bulb, dry bulb, and black-globe temperatures) and supporting data needed for risk management to minimize heat-strain casualties and performance degradation.

14. SUBJECT TERMS
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The most immediate benefit accruing from Phase II development of this device will be the generation of field-usable, low-level decision aids to improve heat-stress risk management to reduce heat-related mission degradation and medical casualties including individual performance. Commercially, the instrumentation can be used to monitor the effects of heat stress reactions on such personnel as hazardous spill workers, firefighters, and toxic chemical handlers.

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Robert J Cilley 4-7-93

PI - Signature Date

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Section 1
PROGRAM OBJECTIVES

Performance degradation and medical casualties resulting from heat strain negatively impact a wide variety of military activities—from training, to combat missions, to Special Operations assignments. Both military and civilian personnel may be called upon to perform dangerous and often strenuous jobs in hostile environments while attired in protective clothing (e.g., fire fighting, hazardous spill cleanup, toxic chemical handling). Operations Desert Shield and Desert Storm emphasized the very real threat of chemical warfare and the concomitant need for troops to be able to function effectively in full MOPP IV individual protective equipment (IPE) without succumbing to heat strain.

A number of environmental conditions (e.g., ambient air, and ground temperatures; wind, solar, and thermal radiation; humidity) contribute to heat stress. Heat strain may be induced by a combination of adverse environmental conditions, activity level (including just being there), and initial physiological state (i.e., acclimation status, hydration); the problem is exacerbated when soldiers must perform in full protective gear.

Evaporation is usually the body's most effective mechanism for eliminating internal body heat generated metabolically by energy expenditure (i.e., work) or environmentally (e.g., solar or reflective radiation).[1] Chemical protective clothing inhibits both insensible (evaporative) and convective and radiation (sensible) heat exchange; for a person lying on the ground, conductance can also be a major factor. When body heat exceeds cooling capability (either because of excessive work load or because of inhibitions placed on the body's cooling mechanisms by protective clothing), increased core temperatures can generate performance degradation, unconsciousness, even death. The effectiveness of predictive models and proactive strategies for mitigating heat-stress medical casualties could be enhanced if continuous quantitative measures of key environmental conditions contributing to heat stress could be obtained.

The objective of the Phase I effort was to determine the feasibility of developing a viable, hand-held environmental health monitor-temperature sensing suite capable of supporting the development of such strategies (based on the premise that wet bulb and globe temperatures provide a limited means to measure radiation, humidity and wind on a temperature scale). Specifically, the Phase I program focused on defining instrumentation system requirements; evaluating temperature-sensing technologies and off-the-shelf instrumentation capable of minimizing the time required to obtain temperature responses while maintaining sensitivities; and establishing a viable

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[1] Significant amounts of heat can also be lost through an impermeable hood [Gonzalez, et al. (1992), ASTM STP, 1133, p. 557+].

system architecture and design concepts for Phase II development. A secondary objective of the program (considered to be desirable, but not essential to demonstrating feasibility of the concept) was to seek methods for improving black-globe response time, thereby improving the potential for effectively preventing or mitigating the severity of medical casualties induced by heat stress.

Section 2
UNDERSTANDING THE PROBLEM

2.1 Heat Strain

A large body of literature exists defining the amount of body heat generated by various activities.[2] For example, when engaged in a sedentary activity, an individual generates about 100W; when engaged in moderate, sustained physical activity, the same individual can generate about 500 W during a three-to-four hour period; when engaged in hard and sustained physical labor this same person can generate more than 700 W in a one-to-two hour period. For the soldier to continue to function and perform the military mission, excess body heat must be dissipated. If not, a medical heat-strain casualty will result.

The body has a complex mechanism for coping with increased heat generation that involves the skin, the central nervous system, and the cardiovascular system; the body's primary method for cooling is perspiration. When body fluids decrease because of excessive sweating and the core temperature increases above an acceptable threshold, vital organs can be damaged. To prevent this, the body shuts down nonessential functions. This physiological response is referred to as heat strain. Initially, performance is degraded, followed by mental confusion, then unconsciousness, and/or death, unless other actions are taken to prevent these occurrences.

There are basically two methods for reducing heat stress, and, thereby, preventing or mitigating heat strain: (1) Reduce the soldier's work load to decrease metabolically generated heat; and/or (2) Increase the soldier's water consumption to enhance the body's evaporative cooling mechanism. While it is not always possible in the battlefield environment to eliminate the factors contributing to heat stress, techniques are available for better managing a soldier's activities (i.e., work/rest cycle) and controlling water intake to reduce the resultant level of heat strain, minimize performance degradation, and decrease the rate of medical casualty generation.

The Combined Arms Exercise (CAX 8-80), which was carried out on the open desert at 29 Palms Marine Corps Base, California, poignantly illustrated the impact of heat-strain casualties on mission effectiveness and pointed to the need for a fieldable, hand-held environmental stress monitor capable of providing an hour-by-hour assessment of heat-stress factors that could lead to heat strain. Two principles of operation were confirmed in this exercise: (1) Water should be considered a tactical weapon; and (2) Commanders who incorporated tne impact of heat-strain in their

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[2] Goldman, R.F., "Prediction of Human Heat Tolerance," Environmental Stress, (Eds. L.J. Folinsbee, et. al.), Academic Press, NY, (1978), pg. 53-69.

mission planning and enforced drinking in the absence of thirst maintained a viable and effective fighting unit.

This exercise fully illustrated the point that if a battle exists in a hot and arid climate, the primary ammunition required to complete the mission will be water. To maintain a viable fighting force, military field leaders must manage their troops properly to eliminate heat-strain medical casualties.[3]

2.2 Predictive Models As A Basis For Decision Aids

For over a half a century, several empirical heat stress indices have been developed that are based upon environmental parameters such as ambient temperature, wind speed, radiant energy and absolute humidity. Yaglou[4] developed an effective temperature nomogram that indicated the maximum sustainable metabolic rates for various ET (Environmental Temperature) levels. Belding and Hatch[5] used the ratio of the evaporative cooling required to maintain a sensor's core temperature to the maximum evaporative cooling possible as a Heat Stress Index (HSI). The Wet Bulb Globe Temperature (WBGT) index was developed as an empirical index by Yaglou and Minard[6] for use by Marine Corp training centers. Goldman[2] reviews different methods used to predict human heat tolerance.

The WBGT heat stress index was selected as a standard by DoD[7] and the international community[8] for its simplicity in measurement. The WBGT index is a linear function that relates the weighted averages of three environmental temperatures (dry bulb, natural wet bulb, and black globe). This index represents in a single number the effects of ambient temperature, water vapor in the air (relative humidity), mean radiant temperature, and air velocity

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[3] Morris Kerstein, et al., "Heat-Related Problems in the Desert: The Environment Can Be An Enemy," Military Medicine, Vol. 149, Dec. 1984, pgs. 650-656.

[4] Yaglou, C.P., "Temperature, Humidity and Air Movement in Industries: The Effective Temperature Index.," J. Ind. Hyg., 9(1927), pg. 297.

[5] Belding, H.S. and T.F. Hatch, "Index for Evaluating Heat Stress in Terms of Resulting Physiological Strain," Heating, Piping and Air Cond., 27(1955), pg. 129.

[6] Yaglou, C.P. and D. Minard, "Control of Heat Casualties at Military Training Center," Arch. Indust. Health, 16(1957), pg. 302.

[7] TB Med 175, The Department of the Army, Navy and Air Force, Washington, DC, April 1969.

[8] ISO 7246, Hot Environments - Estimation of Heat Stress on the Working Man, Based on the WBGT-Index, (Wet Bulb Globe Temperature).

The WBGT index is as follows:

$$WBGT = 0.7\,T_{nwb} + 0.2\,T_{bg} + 0.1\,T_{db} \quad (1)$$

where

T_{nwb} = the natural wet bulb temperature, which is obtained by a wet bulb exposed to the natural air velocity (wind) and is naturally aspirated;

T_{bg} = the black globe temperature, which is obtained by the temperature in the center of a 6-inch (15-cm) diameter hollow copper globe with the outside painted with a matte black finish; and

T_{db} = the ambient air temperature obtained by the shaded dry bulb.

The WBGT index has been empirically correlated with various work conditions, and the physical state of the worker (work load, acclimation, etc). A general observation or "rule of thumb"[9] between the WBGT index and work load is that when the WBGT index is less than 80°F (26.7°C), no heat-strain medical casualties should be produced. Values between 80 to 85°F (26.7 to 29.4°C), indicate potential heat-strain-related medical problems, if workers have not been acclimated for five to seven days prior to the exposure for at least two hours per day at that heat-stress index level. At temperatures above 85°F (29.4°C), acclimated personnel may have heat-strain-related problems. At temperatures above 88°F (31.1°C), work by fit acclimated personnel must be limited to eight to ten hours per day.

Several studies have been performed in which the WBGT environmental temperature has been correlated to the prediction of heat-strain medical casualties. As an empirical number, the WBGT attempts to take into account wind speed by using the natural wet bulb temperature. Since the wet bulb temperature does not represent a thermodynamic property, it is not possible to derive the WBGT empirical index from first principles. Thus, some ambiguity is introduced when the WBGT index (based on a calculated value for differing environmental conditions of temperature, humidity, and wind speed) is used to predict heat-strain casualties.

The Air Force modified the weighting factors of the traditional WBGT index to generate a WBGT index for use in the aircraft cockpit environment. The modified index was then configured as a decision-aid table that can be used by the pilot to

[9] Minard, D.H., H.S. Belding, and H.R. Kingston, "Prevention of Heat Casualties (Description of Yaglou Wet Bulb: Globe Temperature Index)," J. Am. Med. Assoc., 165(1957), pg. 1813.

determine if it is safe to fly; if the reading is in the yellow caution area, the pilot can take prescribed precautions to minimize heat-related medical effects.[10]

The U.S. Army Research Institute of Environmental Medicine (USARIEM), is developing a heat-stress predictive model that is based upon first principles and can be correlated to a large database of medical observations[11] using parameters such as rectal temperature,[12] heart rate,[13] and sweat loss.[14] Predictive equations are being developed for individuals as a function of physical work intensity, environmental conditions and particular clothing. These equations have been modified by factors of energy expenditure,[15] heat acclimation,[16] and solar radiant energy loading.[17] Experimental databases, which consider the effects of physical fitness, gender, and state of hydration, are being evaluated by USARIEM.

This comprehensive model generates predictive outputs of (1) the expected work-rest cycle, (2) the maximum sustained physical work time for a given rate of heat-strain medical casualties, and (3) the amount of water required to maintain the work-rest cycle. Input required by the model includes several environmental parameters such as dry-bulb temperature, relative humidity (aspirated), wind speed, and the mean radiant energy.

The operational objective is to use the WBGT index or the new USARIEM heat-stress model in a hand-held environmental health monitor-temperature suite that will

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[10] R.F. Stribley and S.S. Nunneley, "Fighter Index of Thermal Stress: Development of Interim Guidance for Hot-Weather USAF Operations," SAM-TR-87-6, 1987.

[11] Pandolf, K.B., L.A. Stroschein, L.L. Drolet, R.R. Gonzalez, and M.N. Sawka, "Prediction Modeling of Physiological Responses and Human Performance in the Heat," Comput. Biol. Med., 16(1986), pg. 319.

[12] Givoni, B., and R.F. Goldman, "Predicting Rectal Temperature Response to Work, Environment, and Clothing," Appl. Physiol., 32(1972), pg. 812.

[13] Givoni, R., and R.F. Goldman, "Predicting Heart Rate Response to Work, Environment, and Clothing," J. Appl. Physiol., 34(1973), pg. 201.

[14] Shapiro, Y., and K.B. Pandolf, R.F. Goldman, "Predicting Sweat Loss Response to Exercise, Environmont and Clothing," Eur. J. Appl. Physiol., 48(1982), pg. 83.

[15] Pandolf, K.B., B. Givoni, and R.F. Goldman, "Predicting Energy Expenditure with Loads While Standing or Walking Very Slowly," J. Appl. Physiol., 43(1977), pg. 577.

[16] Givoni, B., R.F. Goldman, "Predicting Effects of Heat Acclimatization on Heart Rate and Rectal Temperature," J. Appl. Physiol., 35(1973), pg. 875.

[17] Breckenridge, J.R. and R.F. Goldman, "Solar Heat Load in Man," J. Appl. Physiol., 31(1971), pg. 659.

measure the appropriate environmental temperatures and predict the effect of heat stress. The primary output will be the work-rest cycle and the maximum allowable sustained work period to permit proper management of heat strain in planning and mission performance. Recommended work/duty cycles and water consumption requirements can be factored into logistics planning. This information must be presented in a format suitable for use as a decision aid that will assist the soldier in understanding the heat-stress related options and in making the correct operational decisions.

2.3 Temperature Measurement

2.3.1 Temperature Measurement Methodology

There are several different methods for measuring temperature; each has its advantages and disadvantages.

Various electronic devices have been developed for the measurement of temperature within the range of sensitivity required for this program: resistive wire, thermistor, and thermocouple.

The electrical conductance of material is known to be a function of temperature and can be used as a method of measuring temperature. A piece of wire of a given length and diameter will change its resistance (1/conductance) as a function of temperature. The wire resistance can be calibrated to a given temperature value such that an accurate temperature sensor can be built.

For most materials, electrical resistance increases as temperature increases. Thermistors operate on the same basic principle, except that resistance in most types decreases as the temperature increases. A thermistor is a temperature probe whose resistance across electrical terminals is governed by the temperature of the sensing material between the terminals. The magnitude of this change in resistance is a function of the sensing material selected and its temperature.

A thermocouple is a thermal junction of two dissimilar metals; when they are in contact, they develop a difference in potential. In use, a complete circuit must be made of the two metals, so that two such thermal junctions are formed. If all parts of the circuit are at the same temperature, no electrical current flows, since the EMFs at the two junctions are equal and in opposite directions around the circuit. If the temperature of one junction is changed, the EMF across this junction in increased, the two junctions no longer balance, and the net EMF acting around the circuit can be measured with a potentiometer inserted in the circuit. This net EMF (measured by the potential difference) is a measure of the temperature of one junction relative to that of the other, which is usually taken as a reference and held at a known temperature.

Commercially available thermocouples and thermistors cover a wide range of environmental temperatures. In all cases, the temperature probes must be calibrated to a range of temperature standards that will allow the changes in the electrical properties of a dissimilar metal junction or a resistive type material to be converted to a temperature value. In most cases, in the temperature range that is of concern for an environmental health monitor, this relationship will be essentially linear.

2.3.2 Measurement Devices

2.3.2.1 Dry Bulb Measurement

The dry bulb temperature is a measurement of the ambient air temperature. The measurement is relatively simple and can be made using any of the temperature measurement techniques described above, but precautions must be taken to eliminate the potential for considerable error.

An issue of concern in the measurement of the dry bulb temperature is to protect the sensor from direct and diffuse radiant energy. This requires that the sensor be properly shielded to eliminate any direct solar, diffuse solar and radiation (IR) energy impingement. This is accomplished by placing a number of radiation barriers between the sensor and the environment. One must design the shielding configuration such that there is adequate air flow through the shielding mechanism and around the sensor to allow for temperature equilibrium to be reached by natural convection. The air flow around the dry bulb sensor can also be accomplished by forced ventilation.

The sensor must also be isolated from the surround such that thermal equilibrium can be reached in a reasonable time and not be adversely influenced by IR thermal characteristics of the surrounding walls and sensor support mechanism. If thermal isolation is not properly maintained, then the temperature reading is a mixture of the temperature of the ambient air and the temperature of the surrounding materials.

2.3.2.2 Wet Bulb Measurement

The wet bulb measurement enables determination of the amount of water that is contained in the air and is required to determine the potential for transfer of heat by evaporation from a person. A high humidity value reduces the amount of evaporation of sweat, and, thus, increases the thermal stress. There are two different humidity measurements: forced aspirated and naturally aspirated wet bulb.

In either case, the wet bulb temperature is measured using a temperature probe that is covered by a water-moistened wick. When air is forced to flow over the

surface of the wet wick, evaporation will occur, the wick will cool, and a reduced temperature will be indicated by the temperature probe. The purpose of using forced air flow around the wet bulb sensor is to maximize the evaporative cooling at very low windspeeds and to overcome possible effects of heat storage or reduced evaporation rate by eliminating the presence of an insulating film of still air about the sensor.[2]

The resulting forced aspirated or psychrometric wet bulb temperature can be converted to an equivalent relative humidity using a psychrometric chart and the dry bulb temperature. The relative humidity, itself, is the ratio of the actual partial pressure of the water vapor in the air to the saturation pressure for water vapor at the prevailing (dry bulb) temperature of the air-vapor mixture. These partial pressures can, in turn, be converted into parts by mass values of the components (water and air) and expressed in terms of specific humidity—i.e., the ratio of the mass of water vapor to mass of (dry) air in the mixture—by using the molecular weights of water and dry air.[18]

The humidity and water content of the air can also be determined in other ways. Optical and electrical hygrometers, for example, can be used to measure the dew point temperature. This is the temperature at which a mixture of air and water vapor becomes fully saturated (and vapor condensation begins on a cooled surface) when the mixture is cooled at constant pressure from an unsaturated state. Optical hydrometers typically measure the temperature of a mirror, which has been cooled just enough for dew formation to occur on its surface. Electrical hygrometers, on the other hand, measure the change in electrical conductivity of a material when water condenses (at the dew point) on its surface(s).

The dew point temperature can be converted to an equivalent relative humidity (as noted previously for the case of wet bulb temperature), using a psychrometric chart and the dry bulb temperature.

The property of human hair, which will deform or elongate based upon the amount of water adsorbed, has also been used as a basis for measurement of humidity. This change in elongation of certain organic materials is caused by the change of the amount of liquid water in the pores of these porous materials.

The natural (or naturally aspirated) wet bulb temperature is measured using a wet bulb sensor, which is cooled by the natural air flow of the wind, rather than by a forced aspirated air flow. As such, this temperature is related to the amount of evaporation that a person will experience in the natural air flow, and not necessarily the maximum amount of evaporation that a person can experience. This natural wet

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[18] Mooney, D.A., Mechanical Engineering Thermodynamics, Prentice-Hall, Inc., New York, 1953, pg. 200.

bulb temperature is the value that must be determined for the WBGT heat stress calculation.

2.3.2.3. Black Globe Measurement

The black globe thermometer consists of a relatively thin-walled metallic sphere with a blackened outer surface and with a temperature sensor located inside at the globe center. The standard sized globe has a diameter of six (6) inches (15 cm) and is blackened either by using an electro-chemical coating or a matte black paint. The centrally located temperature sensor actually measures the temperature of air within the sealed globe. At thermal equilibrium, however, this centrally measured black globe temperature is a function of the ambient (outside) air temperature, the radiation incident on the globe and the wind speed. A mean radiant temperature can be calculated[19] using the globe and air temperature together with the wind speed.

The 6-inch (15-cm) diameter standard globe[20] has been used in the past for the determination of the black globe temperature component of the WBGT heat stress value. Recently, the use of a smaller globe has allowed the equipment package, which also contains a dry bulb and a wet bulb, to be smaller. However, the package is still not as small as desired.

The Botsball,[21] a variation of the black globe temperature probe, consists of a wetted surface black globe with an analog dial thermometer attached to the center of the globe. The dial is marked with green, yellow, and red temperature regions that correspond to the WBGT heat-stress-related values. When the temperature dial is in the green area, there is no danger of a heat-stress-related medical casualty; the yellow area indicates potential for heat stress, and the red area of the dial indicates that heat-stress problems will occur unless work/rest ratio and water consumption is managed properly.

Imaging and Sensing Technology (IST) has developed a black globe based on the theory that a 1-5/8-inch (4.1-cm) black globe will generate a value that is two-thirds the standard black globe temperature and one-third the dry bulb temperature.

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[19] Santee, W.R., and R.R. Gonzalez, "Characteristics of the Thermal Environment," Human Performance Physiology and Environmental Medicine at Terrestrial Extremes, (Eds. K.B. Pandolf, M.N. Sawka and R.R. Gonzalez), Benchmark Press, 1988, pg. 1-43.

[20] Vernon, H.M., "The Measurement of Radiant Heat in Relation to Human Comfort," J. Industrial Hygiene, 14 (1932), pg. 95.

[21] Botsford, J.H., "A Wet Globe Thermometer for Environmental Heat Measurement," Am. Ind. Hyg. Assoc. J. 32 (1971), pg. 1.

This unit is commercially available, but is large, bulky and expensive. Other firms [e.g., Yellow Springs Instrument (YSI) and Brüel and Kjaer (B&K)] also market WBGT measurement equipment.

Section 3
TEST METHODOLOGY

3.1 Test Objectives

The goal of the laboratory test program was to evaluate the viability of replacing the analog-integrated, standard black globe thermometer with a digitally integrated, miniature globe featuring multiple, surface-mounted thermosensors.

To meet this objective, a simplified experimental test chamber was used to compare the temperature and equilibrium time responses of the standard or analog black-globe thermometer (ABGT) with the following:

- A 2.25-inch diameter "miniature" ABGT; and
- Various experimental configurations of the digitally integrated, surface-mounted, thermal sensor globe (DBGT).

3.2 Test Configuration

3.2.1 Environmental Test Chamber

The Environmental Test Chamber was designed to evaluate the performance of the miniature analog black globe and the digital black globe using the 6-inch (15-cm) Vernon black globe thermometer as a reference. The Vertical Environmental Test chamber consisted of three parts as shown in Figure 3-1: the lights at the top to simulate a radiant solar input; a test section in the central region, which contained the analog or digital globe thermal sensors being evaluated; and a fan and airflow straightening baffles at the bottom to draw air through the chamber without inducing excessive turbulence or swirl into the air flow in the test section. An open, vertical cylindrical sampling duct-type chamber configuration was chosen to further reduce asymmetries in the air temperature and flow at the test section, which might otherwise arise from effects of buoyancy and convection of air heated by radiation from the lights.

The radiant source consisted of three 150-Watt flood lights that were mounted symmetrically about the vertical axis of the duct and were located 44.5 inches (113 cm) above the center point axis of the experimental globe thermometers. Electrical power to the lights was supplied unregulated, directly from the mains. Voltage regulation was not employed since the purpose of the tests was to explore the overall effect of radiation on the sensors over periods of many minutes. Radiation variations arising from short-term, line-voltage fluctuations were expected to appear as

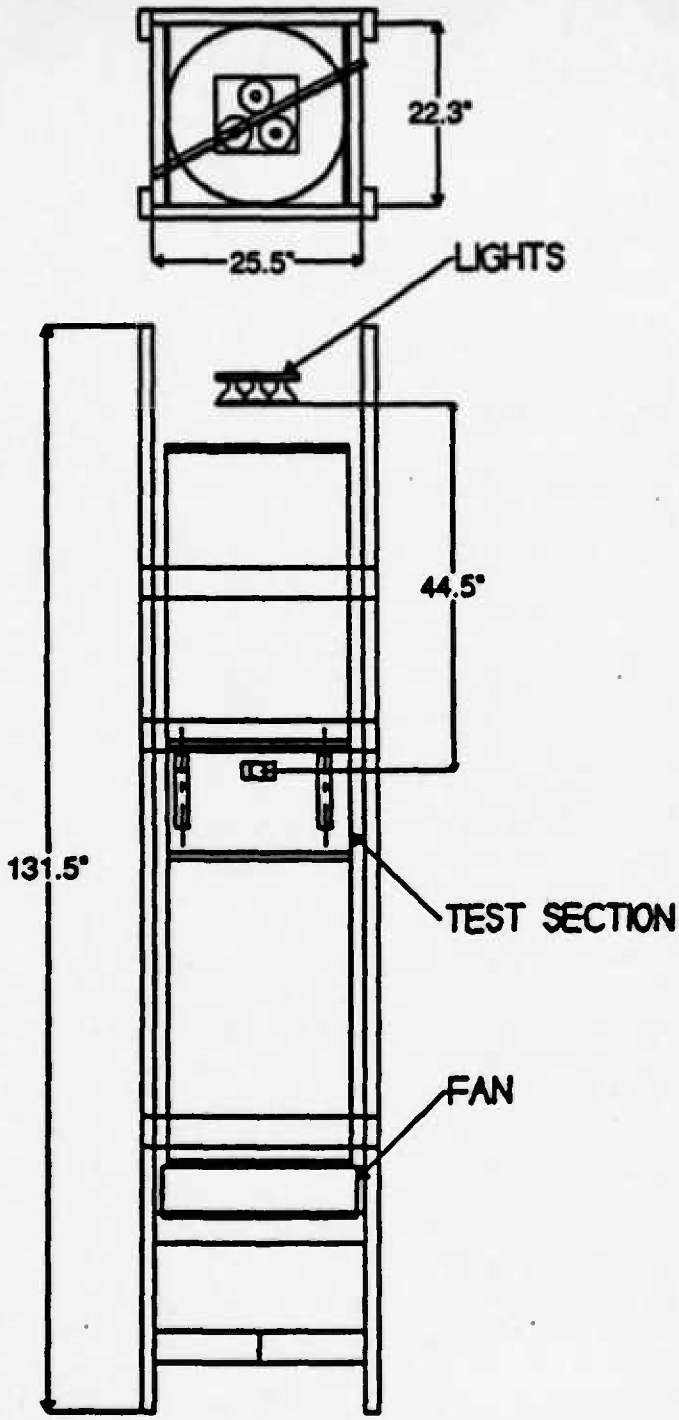


Figure 3-1. Diagram of Experimental Test Chamber

thermal noise on the temperatures indicated by the sensors. Typical rms values of the local 120-volt line fluctuations were about 0.4 volts, or 0.33 percent. Corresponding fluctuations for tungsten filament vacuum lamps were calculated to be about 1.2 percent for the total luminous flux and about 0.5 percent for the total radiant energy (visible and infrared).[22] While these values are inadequate for precision photometry or radiometry, they were considered to be adequate for the Phase I exploratory effort.

The test chamber was constructed from three 21.75-inch (55.2-cm) interior diameter (ID) fiber drums with a 0.125-inch (0.32-cm) wall thickness. The upper section, (above the test section) was 36.5 inches (92.7 cm) long, and the lower section (below the test section) was 38 inches (96.5 cm) long.

The center test section was 13 inches (33.0 cm) long. The center axis of the test temperature probes was 44 inches (111.7 cm) from the radiant source and 48 inches (121.0 cm) from the fan. The test probe was placed in the center of the test section with the control dry bulb placed 5 inches (12.7 cm) off center in the same plane perpendicular to the length of the environmental test chamber. The test section configuration with the test probe under evaluation (black globe) and the control probe (shaded dry bulb) is illustrated in Figure 3-2. The dry bulb measurement was used as an internal control in order that different experiments could be scaled based upon their ambient dry bulb temperature. The intent of the scaling was to be able to compare test runs with a given radiant source (three 150-W flood lights) and at different wind speeds.

The chamber was placed in a vertical position to assist in maintaining a uniform temperature and wind distribution across the test section. The fan had three settings that were representative of wind speeds of 1.5, 2.5., and 3.4 m/s, respectively, as measured at the globe axis position in the test section. To eliminate turbulent air effects, four 10-inch-long (25.4-cm) cardboard baffles were placed near the fan.

3.2.2 Monitoring of Wind Speed

The wind speed was monitored using an Omega Air Speed Indicator (Model HH-F10) mounted on a rod (dowel). The wind speed monitor was placed at selected locations just above the test plane perpendicular to the direction of air flow. The wind profile with and without the test probe in place varied less than 5%. The wind speed was measured as a control.

[22] Moon, P., The Scientific Basis of Illuminating Engineering, Dover, New York, 1961, pg. 160-164.

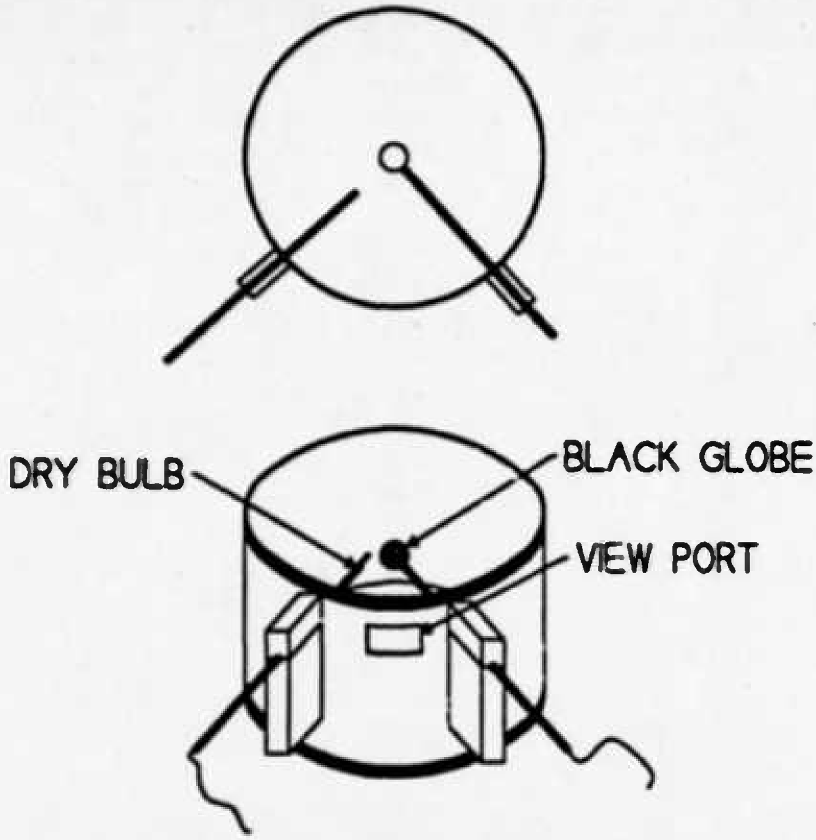


Figure 3-2. Experimental Test Section

3.2.3 Thermal Sensors

The thermistors used as the basic thermal sensors for the dry bulb, wet bulb, analog black globe and digital black globe temperature measurements under this effort were Unitherm Thermochip Type DC95F103W.[23] These precalibrated interchangeable units are epoxy-coated for stability and are built to close tolerances for resistance-temperature curve tracking of about ± 0.2°C over the temperature range of 0°C to 70°C. The resistance of this particular type of thermistor is nominally 10,000 ohms. The maximum bulb diameter of thermistors of this series type is 0.095 inches (2.4 mm), and the bulb shape is slightly ellipsoidal. These units may be used over the temperature range of -80°C to 150°C, but the manufacturer cautions that resistance shifts and degraded stability will result if the devices are subjected to

[23] Thermometrics, Inc., 808 U.S. Highway 1, Edison, NJ, 08817.

temperatures greater than 105°C. The time response of this thermistor in still air is 10 seconds.

3.2.4 Data Acquisition System (DAS)

The temperature data were recorded using a personal computer modified for this purpose. An I/O interface board was designed and fabricated for facilitating a 12-bit resolution analog-to-digital converter with a multiplexing circuitry producing 32 channels of analog input capability. Figure 3-3 is a block diagram of the 32-channel data acquisition system. The DAS controlling software was written for diagnostic testing of the I/O board functions and the acquisition of data. The system was designed to take 2048 data points per channel (with a variable sampling rate). Each channel was sampled at a rate of once per second for the majority of the data collection.

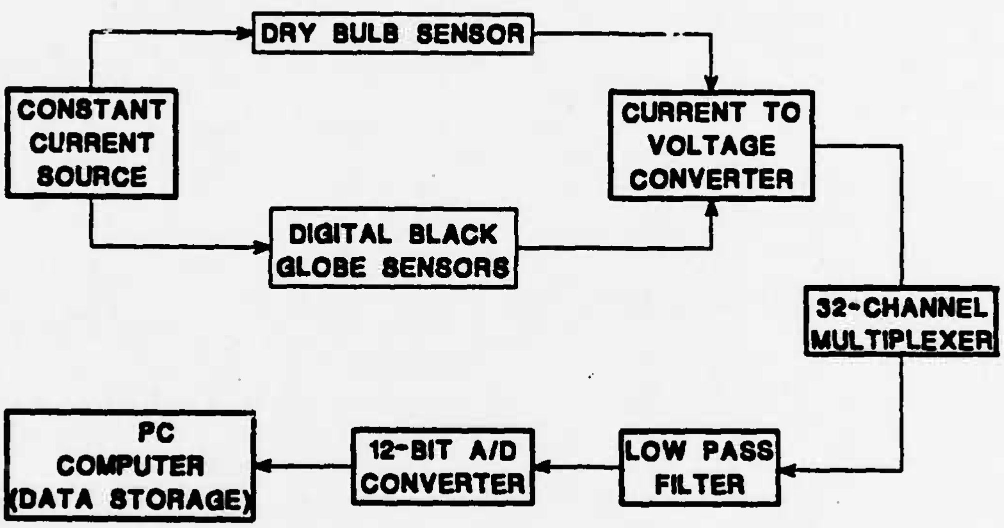


Figure 3-3. Block Diagram of Data Acquisition System

The instrumentation lines consisted of a single 34-conductor ribbon cable, which connected individual precalibrated thermistor sensors to their respective input channels. Calibration of the DAS electronics was maintained through periodic testing and comparison against NBS-traceable secondary instrumentation.

Software was written that converted the sensor data as recorded by the DAS in terms of voltage to the corresponding temperature value using a three-point-calibration curve fit. Offset and scaling factors inherent to the DAS were determined and incorporated with the data calibration. The conversion of sensor voltage to temperature for any channel is stated as:

$$T_n = [1-(a_o + a_1 \ln R_{T,n} + a_3 (\ln R_{T,n})^3)] - T_c \quad (2)$$

with

$$R_{T,n} = K_{C,n} / [V_{O,n} - V_{OS,n}] \quad (3)$$

where

a_o, a_1, a_3 =	unique constants derived from the thermistor manufacturer[23] Resistance vs Temperature Chart at T=0,16, and 30°C
T_c =	273.15°C
K_c =	DAS calibration constant (gain factor)
V_O =	DAS channel output
V_{OS} =	DAS channel amplifier offset
n =	nth analog channel

The error introduced through data interpolation using the above equation was determined not to exceed the uncertainty of the data acquisition system.

3.3 Temperature Sensors

3.3.1 Analog Black Globe

The analog black globe was constructed from matching spun copper hemispheres. The black globe was attached to a 15-inch (38.1-cm) long, stainless steel support rod with two 3/32-inch (0.24-cm) thick teflon cushions for thermal insulation. A 5/16-inch (0.39-cm) screw was modified to allow for the insertion of a 0.015-inch (0.04-cm) inside diameter (ID) x 0.155-inch (0.39-cm) outside diameter (OD) brass tube, which was used to position a thermistor in the center of the assembled globe. A two-conductor, shielded teflon cable with 26AWG wire was fed through the stainless steel support rod, through the brass tube and adhered in place. The exposed ends of the wires were soldered to the thermistor leads, which were coiled into a spiral. The coils were added as a thermal control. The cable shielding was wrapped at the end of the brass tube and a definite solder connection was made to the brass tube. The exit end of the cable was attached to a two-prong amphenol connector.

The standard 6-inch (15-cm) analog black globe sensor and the 2.25-inch (5.7-cm) analog black globe sensor were assembled in exactly the same way (see Figure 3-4).

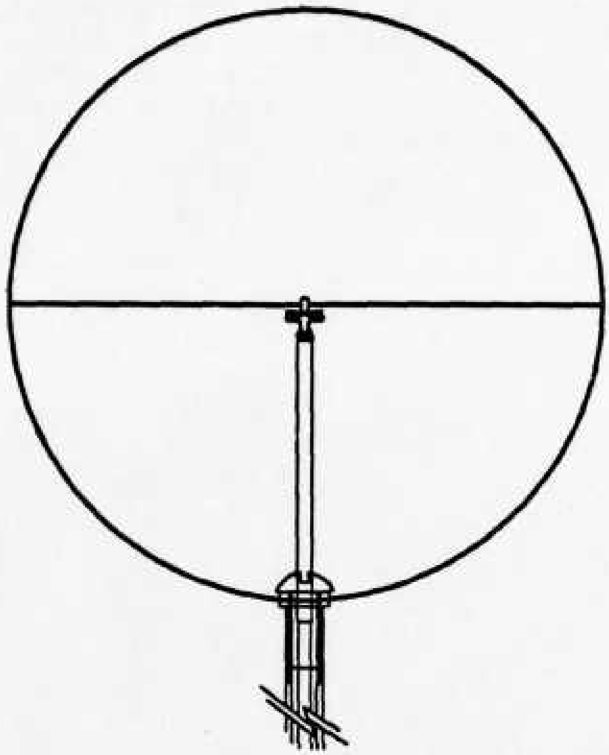


Figure 3-4. Cross Section of Black Globe

3.3.2 Digital Black Globe

The digital black globe sensor was fabricated by attaching 31 individual thermistors on the surface of a 2.25-inch (5.7-cm) diameter, clear plastic sphere. Experimental data were taken with the closed clear plastic globe (DBGT-I), with the clear plastic globe separated to allow for air flow into the interior of the globe (DBGT-II), and with a closed plastic globe coated with high-gloss white paint (DBGT-III).

These different plastic configurations were tested to examine the nature of globe heating in each case. For the clear plastic case, both the inside and outside of the globe (or globe halves) received radiation. For the white-painted globe, the white-coated surface reflected most of the radiation and shielded the interior side of the sphere from radiation.

To mount the surface thermistors, thirty-one 0.095-inch (10.24-cm) diameter holes were placed equidistant from each other over the surface of the globe. The

thermistors were then press fit into each hole from the inside of the globe and were allowed to protrude slightly past the surface of the globe. A 0.003-inch (0.007-cm) brass disc approximately 0.25 inches (10.69 cm) in diameter was then adhered to the surface of the ball such that the center of each disc made contact with the tip of the thermistor sensor. Each disc was then painted with High-Q High Heat No. 1552 Black matte paint. Figure 3-5 illustrates the attachment of the individual surface mounted thermistors.

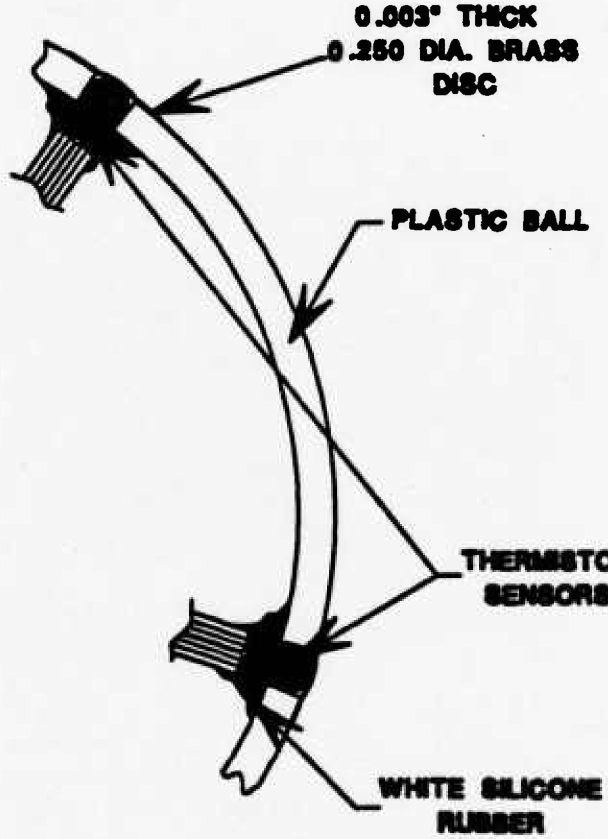


Figure 3-5. Detailed View of DBGT Thermistor Sensor Placement

An 18-inch (45.7-cm) long, 0.375-inch (10.95-cm) diameter brass tube was then attached at the nadir position of the DBGT to serve as a support and electrical feedthrough from the wind tunnel test section to a 32-conductor ribbon cable that connected the sensor to the DAS. Figure 3-6 illustrates the assembly of each half of the DBGT before it was sealed together to form a single globe.

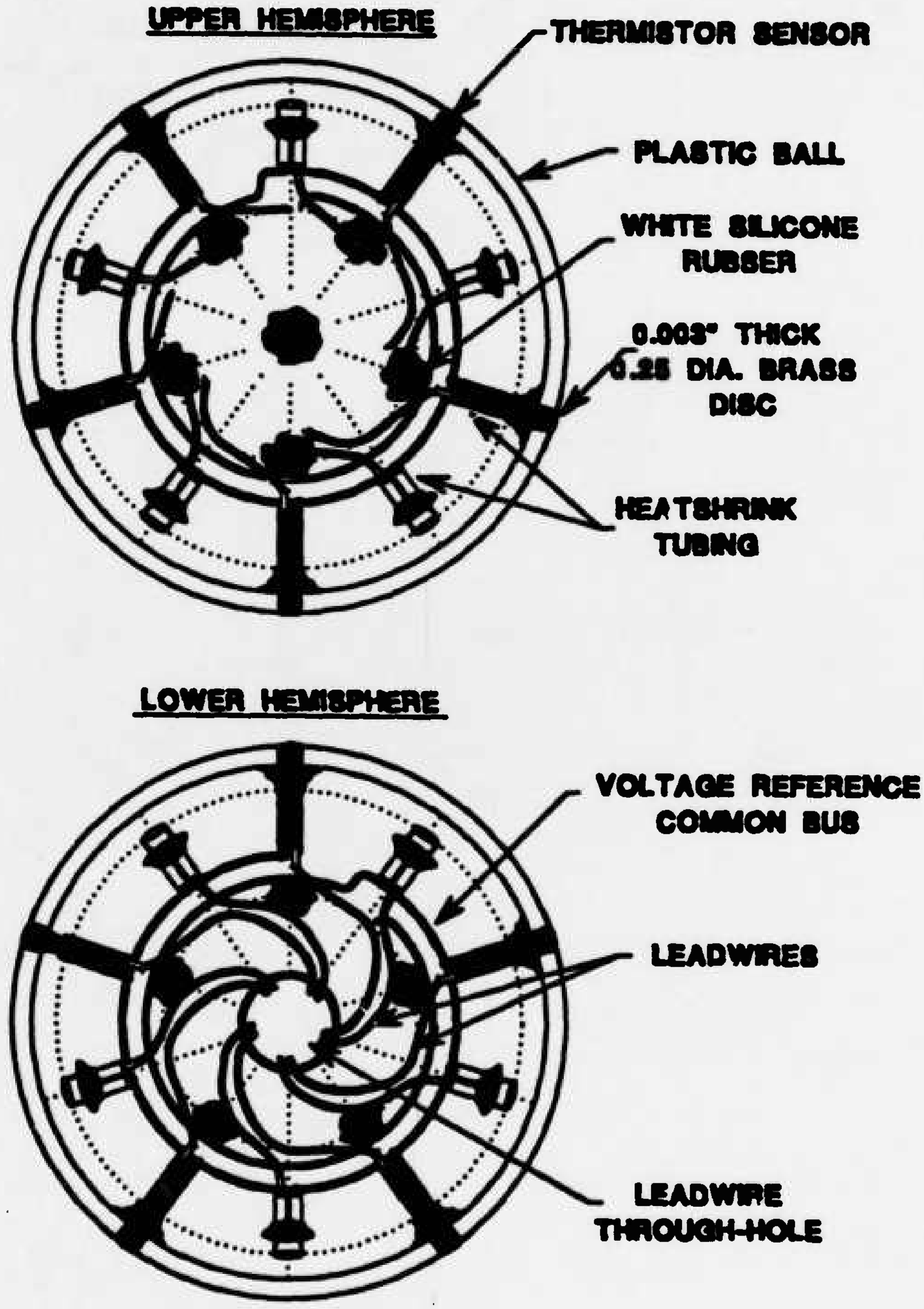


Figure 3-6. Diagram of DBGT Assembly

3.3.3 Dry Bulb

The dry bulb used the same thermistors as were used in the black globe sensors. A thermistor was positioned at the end of a 19-inch (48.3-cm) stainless steel rod, which was cut to provide a shield from the direct radiant energy provided by the three 150-W flood lights. The thermistor was isolated from the stainless steel rod by a 0.312-inch (0.79-cm) diameter, 0.2-inch (0.5-cm) long teflon sleeve, which was adhered to the inner wall of the stainless steel rod. The leads of the thermistor were inserted through this sleeve (via two independent openings placed in the sleeve). The extruding leads were coiled in approximately 0.04-inch (0.10-cm) coils and were attached to the exposed 26 AWG wires in the Teflon[R] insulated cable. The coiled section of the thermistor leads were individually covered with polyolefin shrink tubing. The exiting wire leads were attached to a two-prong amphenol connector.

Section 4
EXPERIMENTAL TEST RESULTS

4.1 Black Globe Thermometer

4.1.1 Analog Black Globe Thermometer (ABGT)

The 6-inch Analog Black Globe Thermometer (ABGT) was used as the baseline reference for determining black-globe temperature. The standard black globe consisted of a thermistor in the center of a black-painted copper sphere 6 inches (15 cm) in diameter. The thermistor resistance values were recorded and converted to temperature using a data acquisition system with signal conditioning.

4.1.1.1 Effect of Radiant Heat

The response curve of the 6-inch ABGT indicated that there were two sources of heat on the black sphere. The dry-bulb temperature profile showed an initial increase with a relative fast time response caused by the radiant input of the heat lamps. The dry bulb temperature then had a slow constant increase in temperature caused by the heating of the walls of the tunnel from the lights used as a solar input. The 6-inch ABGT temperature-time data indicated an initial exponential response followed by linear response.

The equilibrium temperature value and the time to reach the equilibrium temperature was determined to be the point at which the temperature response became linear. This point was then selected as the equilibrium point for the determination of the time to reach equilibrium temperature as a result of the solar radiation (light sources) and the equilibrium temperature value. Figure 4-1 illustrates a typical temperature/time response curve for the 6-inch ABGT and the methodology for determining the equilibrium temperature and time values.

4.1.1.2 Effect of Wind

The air flow around the black globe generates air turbulence near the back side of the globe. In general, the greater the wind velocity, the greater the turbulence. The effect of this airflow is to cool the globe sphere by removing heat through convective cooling. Table 1 illustrates the equilibrium temperature and time for the standard 6-inch (15-cm) diameter black globe. As the wind speed increases, the temperature of the air within the black globe decreases significantly. The average 6-inch ABGT temperature above ambient dropped from 10.3°F (5.7°C) to 6.5°F (3.6°C) as the wind changed from 1.5 m/s to 3.4 m/s.

The wind speed also affected the time to reach the equilibrium temperature. There was a 17% decrease in response time for both the standard 6-inch (15-cm)

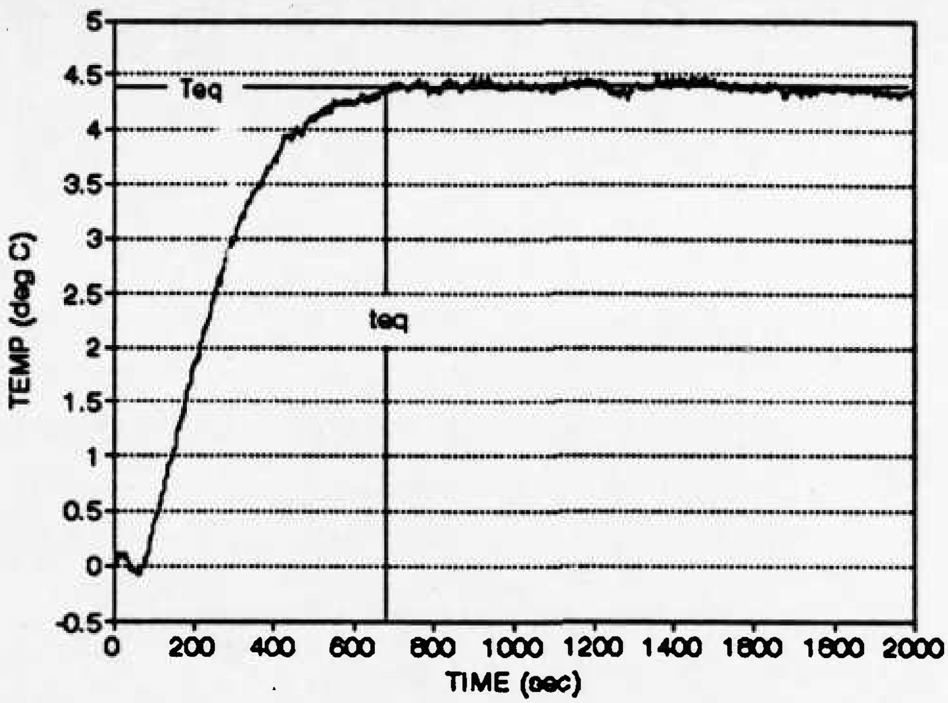


Figure 4-1. Methodology for determining T_{eq} (Temperature at Equilibrium) and t_{eq} (Time to Reach T_{eq}).

diameter black globe thermometer and for the 2.25-inch (5.7-cm) diameter black-globe thermometer (see Table 2) as the air flow increased from 1.5 m/s to 3.4 m/s. Thus, the cooling effect of the wind on both the 6-inch ABGT and the 2.25-inch ABGT response was to decrease the equilibrium temperature and time to reach temperature equilibrium as the air flow around the globe increased. Therefore, the greater the rate of convective heat loss, the faster each sphere reached equilibrium.

4.1.1.3 Effect of Black-Globe Diameter

An analog black globe thermometer was also fabricated from a 2.25-inch (5.7-cm) diameter copper sphere. The resultant temperature increase of the 2.25-inch (5.7-cm) diameter sphere was less than the standard Vernon globe. Table 2 illustrates the equilibrium temperature and time to reach equilibrium temperature for the 2.25-inch (5.7-cm) diameter black globe thermometer. The average 2.25-inch ABGT temperature above ambient was less than the standard black globe thermometer. The equilibrium temperature above ambient of the 2.25-inch (5.7-cm)

Table 1. Temperature-Time Response of the 6-Inch (15-cm) Black Globe Thermometer

WIND (m/s)	T_o (C)	T_{BS} (C)	t_{BS} (Sec)	T_{DS} (C)	t_{DS} (Sec)
3.4	16.8	21.5	700	17.8	350
	17.0	22.5	900	19.0	400
	17.5	22.7	650	19.2	350
2.5	16.8	23.8	850	19.2	425
	17.0	23.9	850	19.4	225
	17.0	24.1	850	19.8	375
1.5	16.5	25.6	920	19.8	500
	17.0	25.4	960	19.7	400
	18.0	26.0	850	20.5	400
	17.5	26.3	900	20.5	400

Table 2. Temperature-Time Response of the 2.25-Inch (5.7-cm) Black Globe Thermometer

WIND (m/s)	T_o (C)	T_{BS} (C)	t_{BS} (Sec)	T_{DS} (C)	t_{DS} (Sec)
3.4	16.0	20.3	610	18.1	300
	17.0	21.2	610	19.1	450
2.5	16.0	21.4	650	18.8	400
	17.0	22.4	750	19.8	400
1.5	16.5	22.8	700	19.7	500
	16.0	22.7	800	19.7	550
	17.5	23.6	700	20.7	600

diameter sphere at 1.5 m/s wind speed was 5.4°F (3.0°C) and fell to 3.8°F (2.1°C) for a wind speed of 3.4 m/s compared to 10.3°F (5.7°C) and 6.5°F (3.6°C), respectively, for the standard black globe sphere. The effect of going to the smaller globe was to decrease the time to reach equilibrium temperature by 16 to 19%.

4.1.1.4 Summary

Table 3 summarizes the range of the experimental data obtained for the standard black globe sphere and the smaller diameter black globe sphere. Also included in the table is the response of a single thermistor painted black. The cross-section of the thermistor is approximately one eighth of an inch. This is the limit in size of a black globe thermometer using the current thermistor. It is included in the table for comparison purposes only.

Table 3. Range of Equilibrium Temperature and Equilibrium Time for Different Black-Globe Configurations as a Function of Wind Speed

Test Probe	Wind Speed: 3.4 M/S	Wind Speed: 2.5 M/S	Wind Speed: 1.5 M/S
15-cm	21.5-22.7 (°C)	23.8-24.1 (°C)	25.4-26.3 (°C)
equilibrium time	650-900 (sec)	850 (sec)	850-960 (sec)
5.7-cm	20.3-21.2 (°C)	21.4-22.4 (°C)	22.7-23.6 (°C)
equilibrium time	610 (sec)	650-750 (sec)	700-800 (sec)
0.3-cm	17.7-18.1 (°C)	17.1-17.3 (°C)	18.1-19.3 (°C)
equilibrium time	25 (sec)	25 (sec)	25 (sec)

The response of the bare thermistor illustrates the minimal effect of wind and convective cooling on the equilibrium temperature value of the thermistor. The response time to reach equilibrium temperature was approximately 25 seconds--essentially the same for all three wind conditions. The time constant for the thermistor was about ten (10) seconds.

4.1.2 Digital Black Globe Thermometer (DBGT)

The Digital Black Globe Thermometer (DBGT) represents an approach to duplicating the integrated temperature reading of a Vernon 6-inch (15-cm) diameter, black globe by measuring temperatures at the surface for various locations on a 2.25-inch (5.7-cm) sphere, and mathematically combining these individual values to obtain an average temperature over the globe. The purpose of the experimental test series was to demonstrate the feasibility of using such digital integration to achieve a combined reading from a miniaturized globe, which will correlate with that taken from the standard black globe.

4.1.2.1 Time Response of the Surface-Embedded Sensors

The thermosensor suite consisted of 31 thermistors embedded in the plastic spherical globe shell such that they had thermal contact with the plastic globe material. Figure 4-2 shows the temperature response of the surface temperature sensors that were (1) nearest the heat source, and (2) furthest from the heat source (shadow).

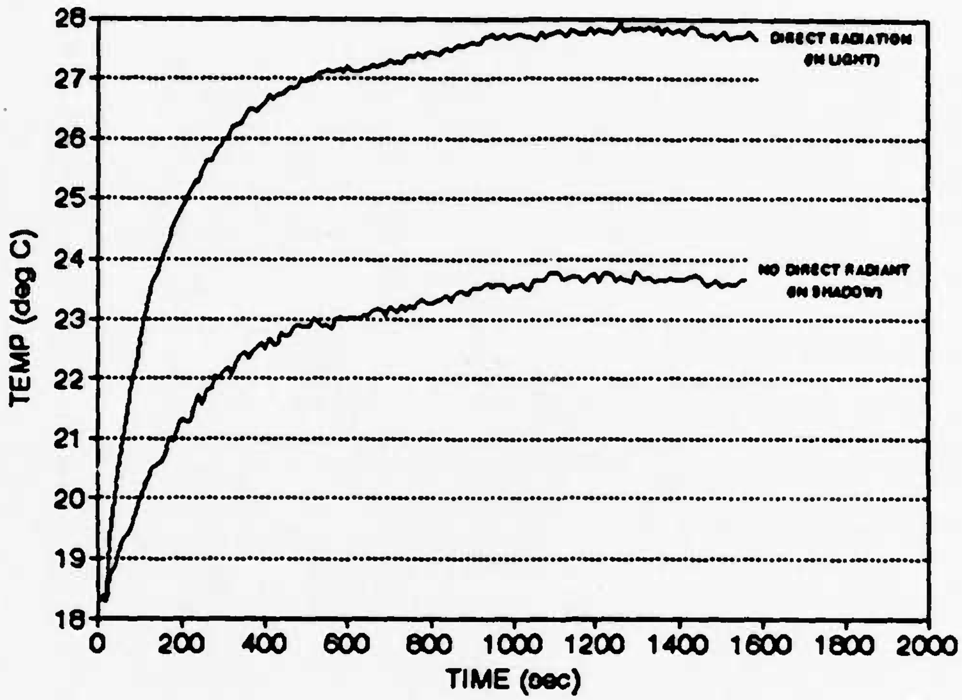


Figure 4-2. Variation of Surface Sensors Depending on Position with Respect to Solar Input

The time response and temperature of thermal sensors fastened to a spherical globe matrix can be affected both by the method of mounting the sensors and by the nature of the matrix material itself.

The thermistors used here were mounted onto the plastic globe by inserting each sensor through a separate small hole with the active tip exposed to the exterior. Each sensor was held in place by heat sealing the plastic around the sensor. The result of using this attachment scheme was that when the sensors were initially exposed to a radiant input, it was observed that both the rate of temperature rise was

slower, and the magnitude of the equilibrium temperature reached was greater (for sensors mounted in the matrix) than the respective rate and magnitude for isolated sensors. The reasons for these observations are relevant to understanding the digital globe and isolated sensor behaviors.

The rate of temperature rise in the sensor embedded in the plastic matrix is slower than for an isolated sensor because more of the incident radiant energy, which is available for absorption, heating and increasing the temperature in the recipient material, is lost from the matrix than from the embedded sensor. This loss occurs by transmission through the clear plastic matrix, or by reflection from the high-gloss white paint of the coated plastic. As a result, heat is initially transferred readily by conduction from the small sensor mounted on the globe to the surrounding plastic. This transfer does not last very long, since the plastic itself tends to be a poor heat-transfer medium and the temperature difference at the plastic-sensor interface approaches zero. This heat transfer to the plastic, however, reduces the early rate of temperature rise in this sensor compared to the rate in an isolated sensor, where the overall convective heat transfer is slower.

The magnitude of the equilibrium temperature reached by the sensor embedded in the plastic matrix is greater than that for an isolated sensor because of two features. First, the heat transfer within a small sensor occurs mainly by conduction and is relatively large in order for the sensor itself to have a short response time. Any heat buildup in an isolated sensor is lost over a period of time by convective heat transfer losses from the sensor surface. In contrast, the heat transfer within a plastic or insulating-type spherical shell—chosen purposely to isolate the individual embedded sensors from one another—is poor; convective heat losses from the outer surface of such a closed sphere are also poor; and heat retention by the globe is significant. Second, there is a somewhat greater surface-to-volume ratio for the isolated sensor as compared to the digital globe, and this tends to enhance the heat losses of the small sensor.

When the thermal sensor was mounted to the surface in such a way that the sensor was raised above the surface of the plastic globe matrix, a lower temperature response was obtained, as illustrated in Figure 4-3. Thus, devising a mechanism for mounting thermal sensors so as to minimize the globe matrix effect is an issue that needs to be addressed and evaluated in a Phase II effort.

4.1.2.2 Surface Temperature Distribution of DBGT

The surface distribution of the DBGT indicates that the surface temperature varies depending on its relationship to the direction of the radiant energy source. The surfaces closest to the radiant energy source (lamps) were the hottest, and the surfaces furthest from the radiant energy source on the back side of the

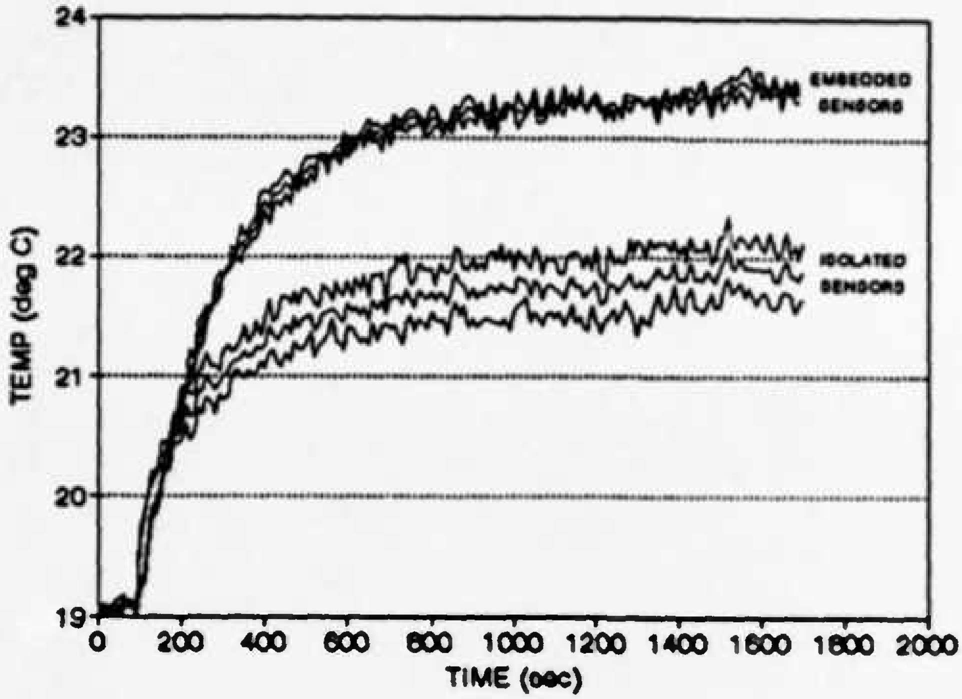


Figure 4-3. Effect of Sensor Mounting Technique on Temperature Measurement

sphere in the shadow were the coolest. Figure 4-4 illustrates the distribution on the sphere of the temperature difference above the dry bulb reference temperature.

4.1.2.3 Integrated Temperature Response

The equilibrium temperature and time response obtained from integrating the temperatures of the individual surface sensors mounted in a closed globe generated a mixed effect from a combination of thermal sensor heating from the radiant source and from the globe plastic matrix itself. The surface sensors measure the total energy received from exterior radiant source(s), as well as thermal input from the radiation-heated plastic globe (including radiation incident on the exterior of the globe, as well as that transmitted through the clear globe and incident on the inside surface), interior air, and interior sensor wiring components. Figure 4-5 illustrates the time response of the temperature difference curve of the digitally integrated surface temperatures of a clear 2.25-inch (5.7-cm) spherical globe and a reference dry bulb (thermistor) sensor. Corresponding temperature difference response curves are shown for the 6-inch (15-cm) and the 2.25-inch (5.7-cm) ABGTs. The temperature

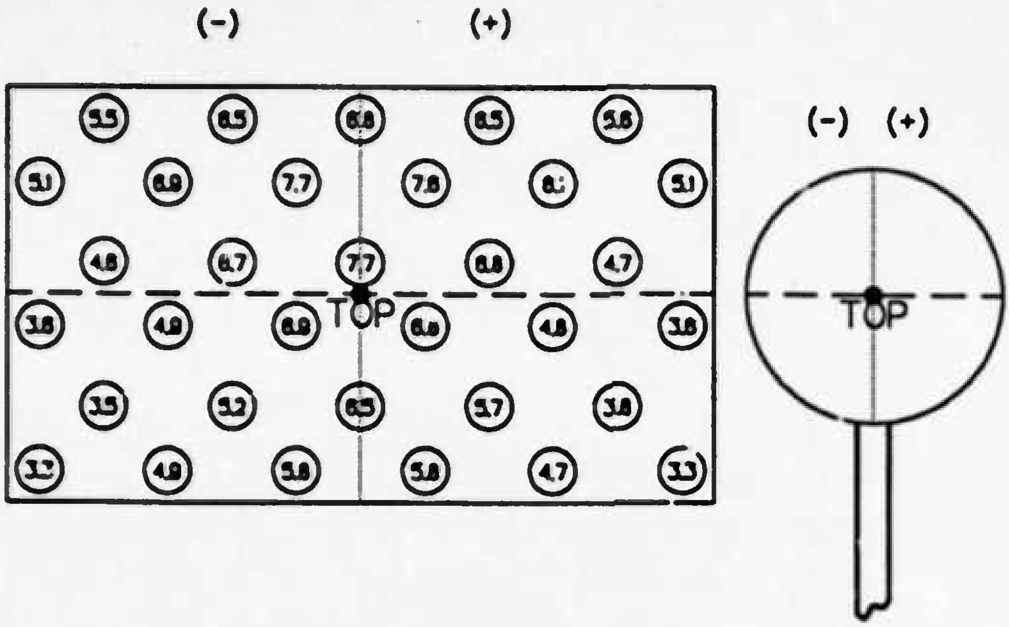


Figure 4-4. Sensor Map of Difference Between Surface Equilibrium Temperature and Dry Bulb for DBGT-I (Dry Bulb=20.1°C, wind=3.4m/s) (Clear Globe)

difference of the DBGT-I fabricated from a clear 2.25-inch (5.7-cm) sphere was greater than that of the standard 6-inch (15-cm) ABGT.

This greater temperature difference in the DBGT-I than the standard AGBT was attributed to greater radiant heating of the interior components of the former. Radiant heating within a standard 6-inch (15-cm) ABGT should be minimal; conduction through the globe to heat the interior air, and convective heating of the inside temperature sensor by this interior air should be the predominant mode of action.

To explore the interior thermal effect upon the surface-mounted sensors of the DBGT-I unit, two techniques were employed. The first technique (DBGT-II) used convective (air flow) cooling of the interior components, while maintaining essentially the same exterior air cooling and radiation input. The second scheme (DBGT-III) used white paint on the surface of the globe to block radiation transmission into the globe interior, and thereby achieve interior cooling. In each case, a significant reduction in the difference between these differential temperature response curves from that obtained with the standard ABGT was expected.

In the first case (DBGT-II), a clear 2.25-inch (5.7-cm) digital globe was split into two hemispheres. The hemispheres were separated by approximately

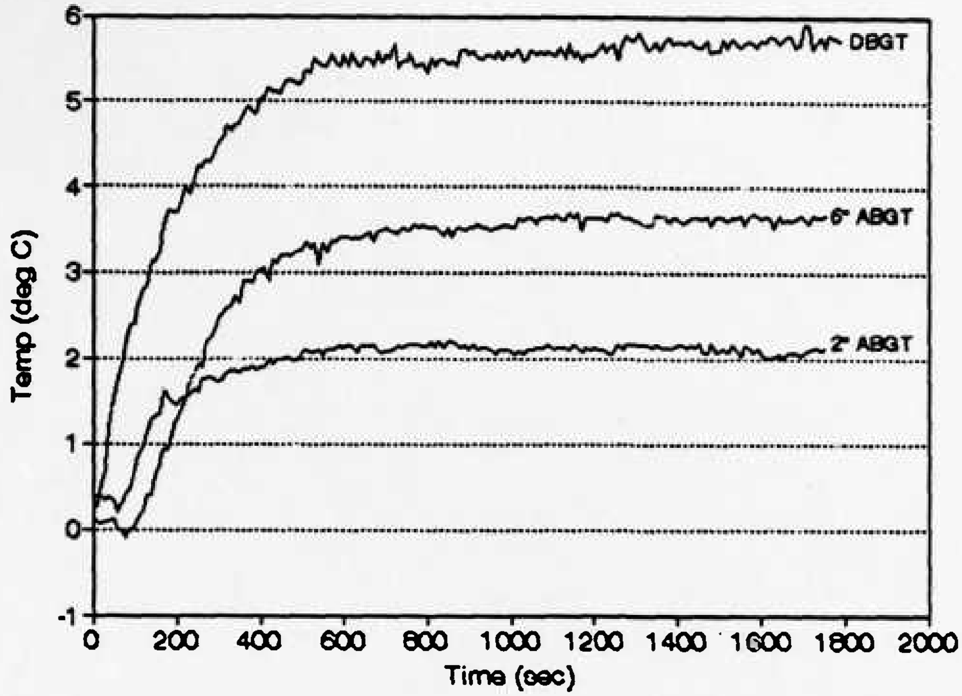


Figure 4-5. Time Response of Temperature Difference Between Selected Globe Thermometers and a Reference Dry Bulb (Thermistor) Sensor (Wind= 3.4 m/s)

four (4) inches (10.0 cm), yet joined with a thermal shield consisting of a highly reflecting aluminum foil half-cylinder shell (with open bottom) placed between the two hemispheres to prevent downward directed radiant energy from reaching their interior without passing through their plastic walls. This split globe allows both radiative heating and convective cooling of the interior components, and, to some extent, of the inside of the plastic shell. The difference temperature response curves are shown in Figure 4-6.

Separating the digital globe into two hemispheres together with using the aluminum foil shield provided access to the air flow and kept the interior of the globe at ambient (dry bulb) temperatures. This prevented excess heating of the globe plastic material and resulted in a lowering of the individual sensor readings, as indicated from the difference between the integrated equilibrium temperature and the dry bulb temperature dropping from approximately 9.7°F (5.4°C) to 2.2°F (1.2°C). The time response to reach equilibrium temperature was also reduced by half (to approximately 300 seconds)---about the same as the dry-bulb temperature response

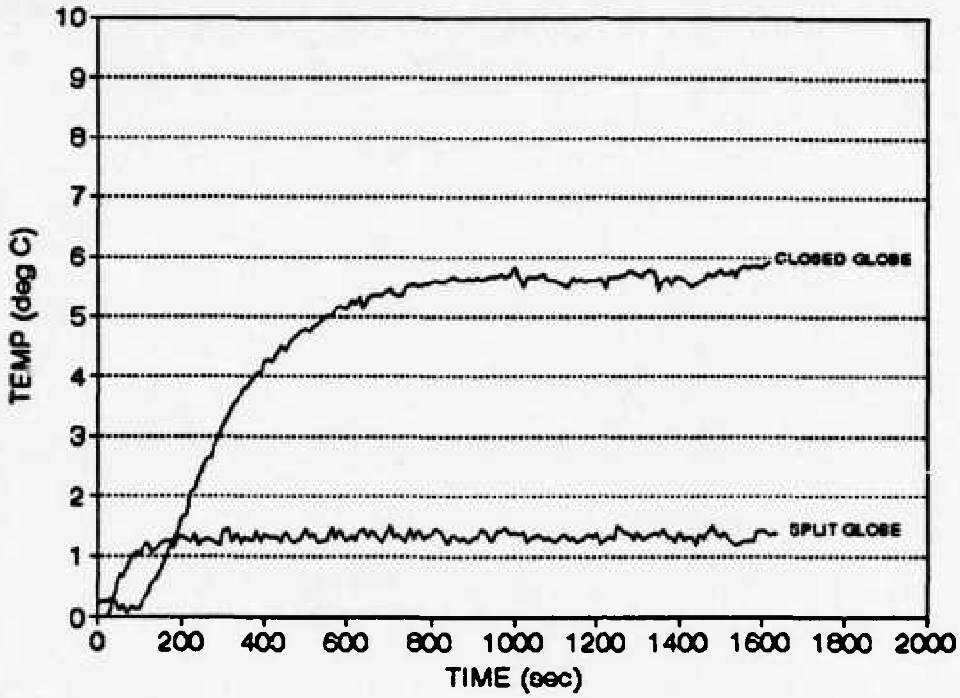


Figure 4-6. Effect of Internal Globe Heating on Surface-Mounted Sensors (Wind = 3.4 m/s)

time. Thus, there is a considerable thermal input caused by the globe being a clear plastic material.

When the globe (DBGT-III) was painted white to reflect as much radiant energy as possible, the equilibrium temperature obtained by integrating the temperature readings of the individual surface-mounted sensors was approximately 4.0°F (2.2°C) above the dry bulb temperature region---essentially the same as the 2.25-inch (5.7-cm) ABGT value of 3.8°F (2.1°C). The time response to reach equilibrium temperature was increased over the split globe to a value of approximately 400 seconds, indicating a residual heating and/or greater buildup of heat from radiant energy to affect the interior temperature of the closed globe.

4.1.3 Comparison of ABGT and DBGT

For a small-diameter globe thermometer to be considered as a feasible alternative to the standard 6-inch (15-cm), black-globe thermometer for use in determining WBGT values, the smaller radiant-energy sensor must provide data that

can be correlated with that received from the standard, 6-inch (15-cm), black-globe thermometer (or will allow calculation of the equivalent mean radiant temperature).

To demonstrate the feasibility of the DBGT approach to miniaturization of an environmental health sensor suite, Veritay adopted a two-step approach to correlation:

1. Correlate the black globe temperature of a 2.25-inch (5.7-cm) globe with the black globe temperature of a 6-inch (15-cm) globe; and

2. Demonstrate the ability of the DBGT-III to perform a temperature integration digitally on the basis of selected globe surface-temperature readings.

Figure 4-7 illustrates the temperature response curves for each of the globe temperature devices as a function of wind speed. Each temperature response curve consists of a similar shape with the temperature reaching an equilibrium temperature value (T_{eq}) within a given time frame (t_{eq}). The primary difference between the three globe responses is in the T_{eq} and t_{eq}. It has been the objective of this program to demonstrate (1) that the three globe equilibrium temperatures can be correlated, and (2) that the time to reach equilibrium temperature is less when the DBGT-III is used than when the larger standard black globe thermometer is used.

In Figure 4-7, it is apparent that small differences exist for initial temperature of the various temperature response curves. This is a result of using an open sampling duct, which drew ambient air from the surrounding region in which the duct was located. The ambient air temperature changes slightly on successive days when tests were run. These small initial temperature variations do not negate the consistency of the temperature differences indicated; additional temperature control maintenance would be desirable for further comparative testing.

4.1.3.1 Comparison of Globe Size

The average equilibrium temperature difference (from the initial temperature) for the 6-inch (15-cm) and the 2.25-inch (5.7-cm) copper analog black-globe thermometers were plotted for three wind speeds as illustrated in Figure 4-8. The range of obtained equilibrium temperature difference values is indicated by the range bars for each wind condition. The figure illustrates the approximate relationship between these copper black-globe thermometers.

The time for the globe interior air to reach equilibrium temperature was decreased from 650 to 960 seconds for the 6-inch (15-cm) ABGT to approximately 610 to 800 seconds for the 2.25-inch (5.7-cm) ABGT, over the range of wind speeds

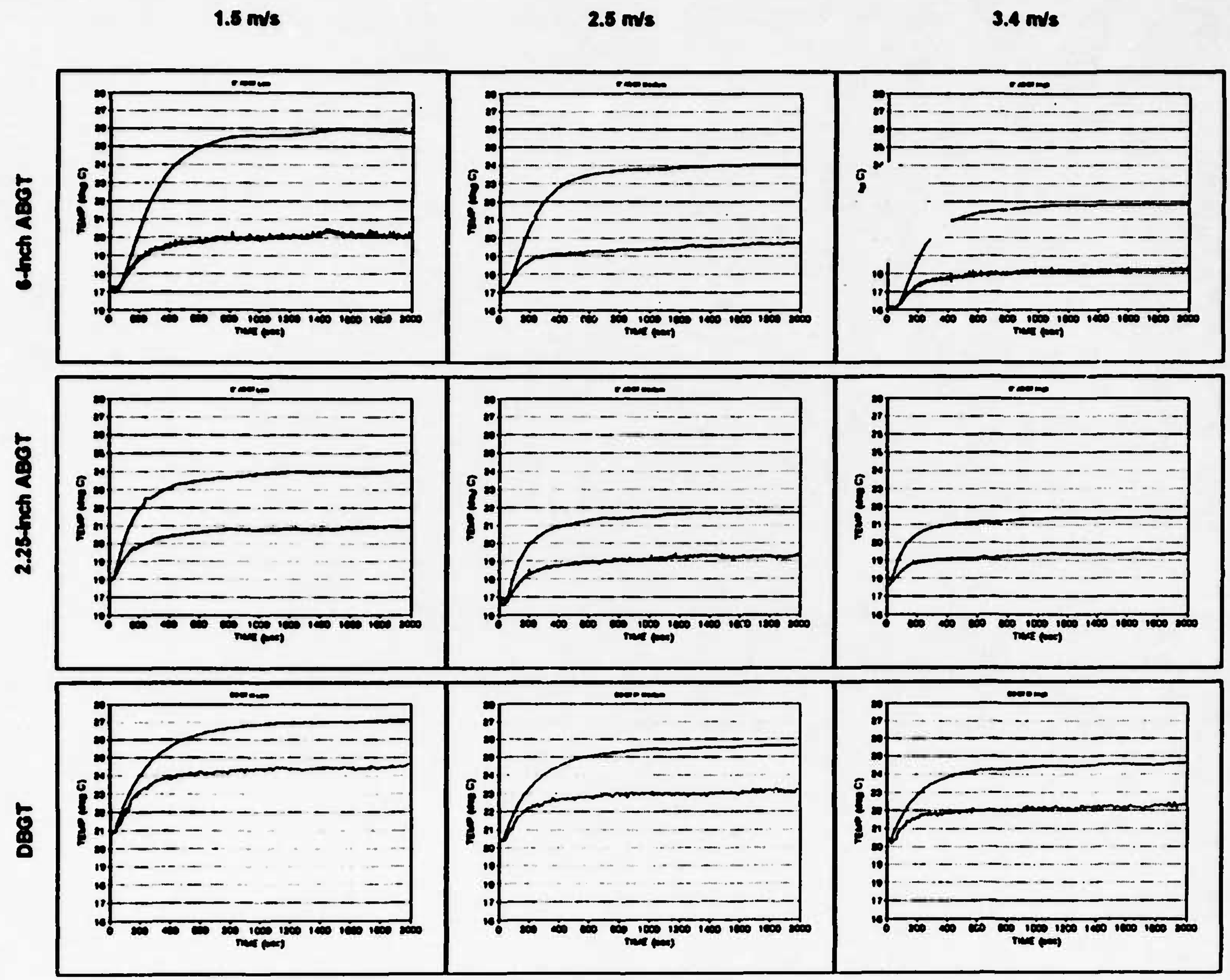


Figure 4-7. Temperature Response Curve of 6-inch (15-cm) ABGT, 2.25-inch (5.7-cm) ABGT, and 2.25-inch (5.7-cm) Digital Black Globe Sensors (Upper Curve-Globe, Lower Curve-Dry Bulb)

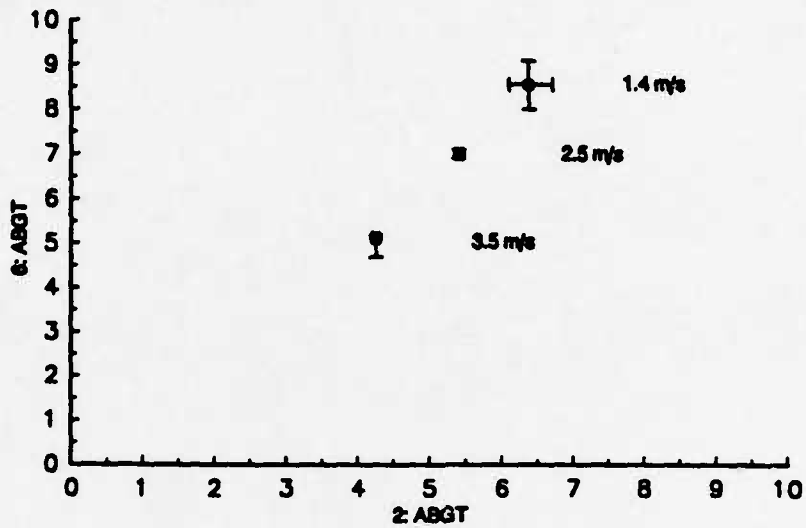


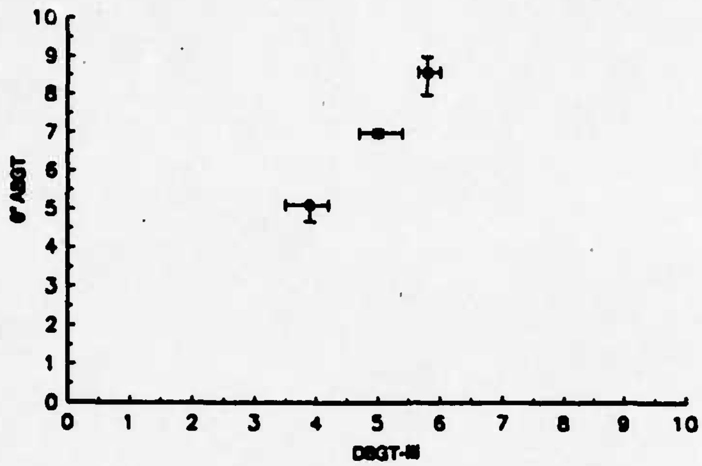
Figure 4-8. T_{eq}-t_e (°C) Temperature Difference of 6-inch (15-cm) ABGT and 2.25-inch (5.7-cm) ABGT at Indicated Wind Speeds (Bars Indicate Range of Data)

examined. The length of the time response is attributed to the time for the copper sphere to come to thermal equilibrium with heating from the radiant input and cooling from the air flow around the copper globe.

4.1.3.2 Comparison of the Analog and Digital Methodology

The average equilibrium temperature difference for the two analog black globe thermometers (ABGTs) is plotted against the average equilibrium temperature difference for the 2.25-inch (5.7-cm) digital white globe thermometer (DBGT-III) in Figure 4-9. The range of obtained equilibrium temperature values is indicated by the range bars for each wind condition.

The comparison of the time for the two different globe configurations to reach thermal equilibrium indicates that the time response of the 6-inch (15-cm) ABGT is approximately 400 seconds, the 2.25-inch (5.7-cm) ABGT about 350 seconds, and the 2.25-inch (5.7-cm) DBGT-III approximately 300 seconds (Figure 4-7). The thermistor



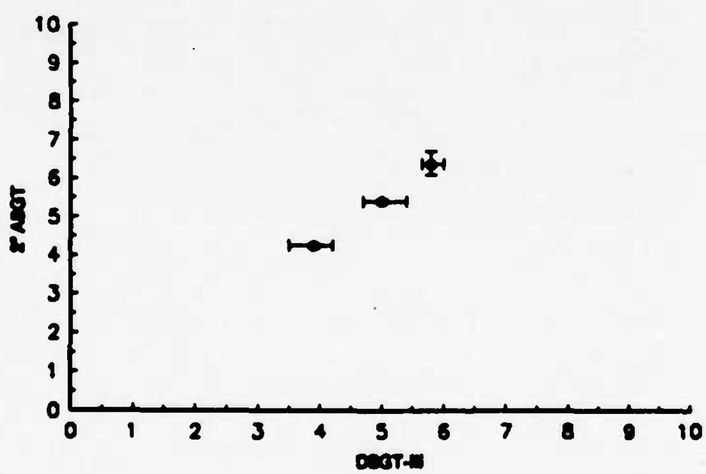


Figure 4-9. $T_{eq}-t_e$(°C) Temperature Difference of 6-inch (15-cm) and 2.25-inch (5.7-cm) ABGT to DBGT (Bars Represent Range of Data)

used in these experiments had a time response of ten (10) seconds, which would allow it to reach thermal equilibrium in approximately 30 seconds if there were no heat gains or losses arising from the connecting leads in the radiation field and in the air stream, respectively. With these latter influences, the actual observed time response was nearly twice this value. The response time of the digital globe thermometer is driven by the rate of heat transfer between the thermistor and the bulk of the globe that is in contact with the thermistor's epoxy support bead. Care in thermally isolating the thermistor can lower the time to reach thermal equilibrium even further.

4.2 Comparison of Analog and Digital Response to a Reference Radiant Energy Source

All experimental runs were made with an approximately constant reference radiant energy source generated from the lamps. The only variables were the temperature of the air supply to the chamber, which was dependent upon the daily ambient temperature, and the air speed, which was set at either a low (1.5m/s), medium (2.5m/s) or high (3.4m/s) setting. Thus, under each experimental condition, the equilibrium temperature difference between the dry-bulb temperature and the value of the analog or digital black globe temperature was caused by the energy input from the lamp source. The variation of globe temperature values as a function of wind speed indicates the effect of air convective cooling caused by the air flow around the globe. Figure 4-10 illustrates the relationship between the analog and the digital black globe thermometer readings.

This comparison shows that the digital approach for measuring the black globe temperature is adequate to allow for miniaturization of the standard analog black globe thermometer with a suite of surface-mounted temperature sensors that are digitally integrated into a black globe temperature reading.

The comparison of the equilibrium temperature difference (T_g-T_{db}) between the 2.25-inch (5.7-cm) analog and the 2.25-inch (5.7-cm) digital black globe temperature (both denoted by the subscript g) and the dry-bulb temperature (designated by the subscript db) indicates an agreement between (T_g-T_{db}) values better than 0.5°F (0.3°C), at each indicated wind speed. These temperature increments in the black globe readings would translate into a difference of less than 0.1°F (0.06°C) in the calculated WBGT value in each case since the black globe temperature is weighted by a factor of 0.2.

Figure 4-10 also compared the preceding equilibrium temperature differences (T_g-T_{db}) for the 2.25-inch (5.7-cm) globe thermometers with the same temperature difference quantity (T_g-T_{db}) for the 6-inch (15-cm) ABGT, at each corresponding wind speed. This combined plot indicates the overall temperature difference relationship between the 6-inch (15-cm) and 2.25-inch (5.7-cm) globe thermometers, as well as the

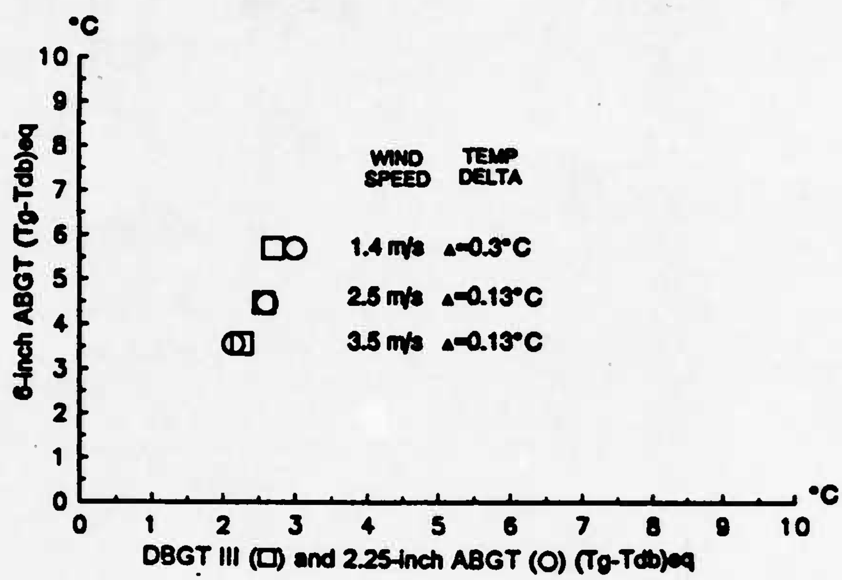


Figure 4-10. Comparison of the Temperature Difference Between the Globe Thermometers and the Dry Bulb at Equilibrium

small temperature increments between the 2.25-inch analog and digital globe thermometers, for the indicated wind speeds.

4.3 Dry Bulb

The dry-bulb thermometer was used as an internal control to monitor the ambient air temperature within the experimental chamber on the same plane as the black globe probe. The temperature-time data indicate that when the radiation source (i.e., light bulbs) is energized, the sensor temperature will rapidly rise to a point and then slowly increase at a constant rate. Figure 4-11 illustrates a typical dry-bulb response curve obtained in the experimental chamber. The temperature response pattern is similar to that observed with the black globe sensors.

The initial temperature of the dry bulb within the chamber is from 1.8-5.4°F (1-3°C) higher than the ambient air temperature at the start of the experimental run. This is attributed to the ambient temperature difference between the experimental

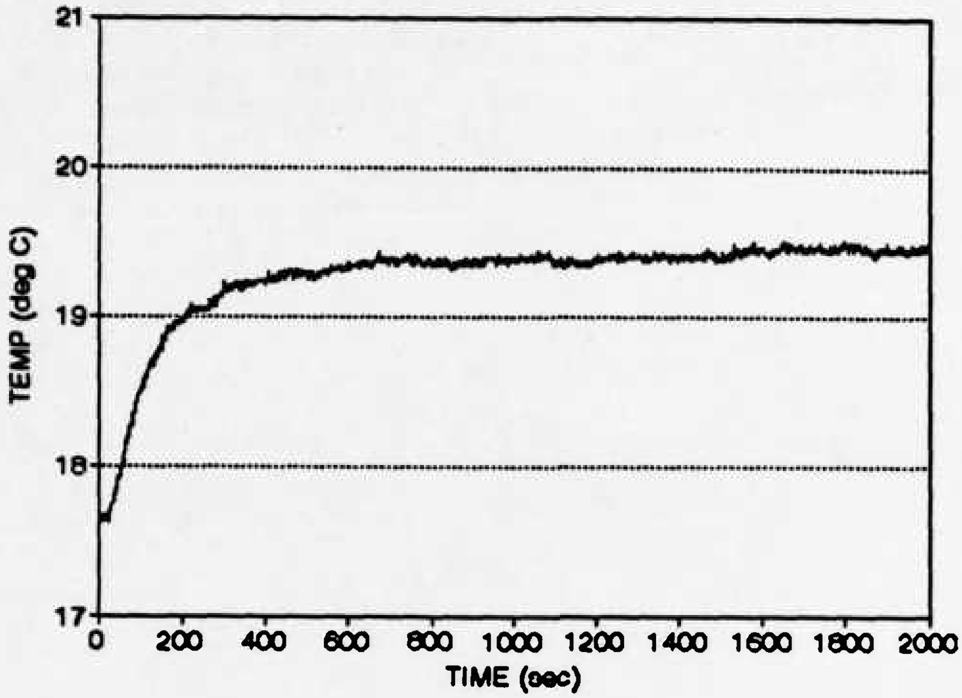


Figure 4-11. Dry Bulb Response Curve

room and the cooler air from the surrounding test area, which was drawn into this room and circulated through the chamber. At the beginning of each experiment, it was noticed that the temperature of the dry bulb would drop when the fan was turned on (generating air flow within the chamber). The temperature would then increase as soon as the heat lamps were turned on because of radiant heating of the air and the chamber walls and convective heat transfer from the lamps. The temperature at t=0 sec was taken to be the value when the heat lamps were activated (as indicated by an increase in the dry-bulb temperature probe).

A wind effect on the dry bulb temperature probe was also observed. As the wind flow increased from 1.5 m/s to 3.5 m/s, the dry bulb temperature would drop from 68.4°F (20.2°C) to 65.5°F (18.6°C) in the presence of radiant heat lamps as a result of the mixing rate of the outside air. The ambient temperature outside of the experimental chamber was typically about 62.2°F (16.8°C), but differed by as much as ± 2°F (1.1°C) from day to day. The ambient air temperature remained essentially constant during any given test run, but occasionally differed slightly from one test run to another.

An unshaded dry-bulb temperature probe was evaluated to determine the temperature response of the thermistor within the experimental chamber. A thermistor was mounted at the end of a metal support probe. The probe was placed in the chamber an equal distance from the radiation source (heat lamps) at the black globe thermometer. The response of the unshaded dry bulb thermosensor indicated that it reached thermal equilibrium; then within 60 seconds, the sensor would show the slow constant increase temperature rise caused by the thermal radiation attributed to the heating of the chamber walls. The thermistors used in these experiments had a time constant of ten (10) seconds.

Section 5
INTEGRATED SYSTEM

5.1 Environmental Health Monitor (EHM) Architecture

5.1.1 System Requirements and Architecture

To be transparent to the performance of the military mission, an environmental health monitor/decision aid for use by operational troops performing risk-management duties in the field must be small (hand-held), rugged, and capable of providing clear and concise answers to specific questions:

- What is the desired work/rest cycle?
- What is the maximum work time for various casualty percentages?
- What is the water requirement in canteens/hour per soldier?

The technical constraints for the measurement of the different temperature values needed to satisfy the computational needs for WBGT dictates the physical configurational system requirements. This includes consideration of the size of the sensors; their access to, or protection from, environmental elements (e.g., wind and radiant energy); and their temperature sensitivity. The operational use of the environmental health monitor by troops in the field will dictate system requirements for built-in testing (BIT), input/output (I/O), and size/weight. The system operational software must be designed to allow the environmental health monitor to be operated by personnel with minimal reading/comprehension capabilities and minimal training.

Table 4 provides operational and physical characteristic objectives for an integrated environmental health monitor capable of generating functional, heat-stress-related, decision-aid information of value in achieving military mission objectives with an acceptable level of medical casualties. To meet these objectives, Veritay has adopted an integrated systems approach to the development of a viable systems architecture.

Table 4. Operational and Physical Characteristics Objectives

Parameter	Objective
Temperature sensitivity	< 0.5°C (1°F)
Response time-initial	
Dry bulb	1 minute
Wet bulb	5 minutes
Black Globe	5 minutes

Parameter	Objective
Response time-continuous	
Dry bulb	0.25 minute
Wet bulb	2-3 minutes
Black Globe(Digital)	1 minute (limited by wind natural variability)
Mission time	72 hours (intermittent) 24 hours (continuous)
Physical configuration size	Hand-held (4"H x 2"W x 1.3"D with 2" globe on top)
Weight (max)	Two-pounds
Water volume	40 ml
Power	Battery (internal)
I/O configuration	
Display	Two-line LCD
Input	Membrane keypad
I/O requirements	
Manual input	A. Activity- work load (watts) duration (minutes) B. Clothing (MOPP level + other) C. Acclimation (days in environment)
Instrumentation inputs	A. Dry bulb temperature B. Natural wet bulb temperature C. Black globe temperature
Display output	A. Work/rest ratio B. Water usage (canteens/hr) C. Max. work load (for different % casualty -10, 25, 50, 75%)
Hardness	A. NBC contamination survivable B. MIL-STD-810D environmental
Logistics	
Maintenance concept	A. Field replaceable unit B. Depot - replace with disposable modules C. Battery replacement IAW battery specification
Calibration concept	At time of manufacture
Production costs	Less than $900 in large quantities ($600 goal)

5.1.2 Architecture Subsystems/Components

The integrated system architecture consists of five subsystems:

- Temperature Sensing Subsystem
- Data-Acquisition Subsystem
- Computational/Model Subsystem
- System Controller Subsystem
- System Packaging Subsystem

These subsystems are defined by their functionality.

The development of each of the subsystems was based upon design criteria derived from the allocation of the functional, technical, and operational system objectives and requirements. From this allocation, design evaluation factors were developed that are based upon the ability of the integrated system to first perform its primary mission (i.e., to measure environmental temperatures), calculate WBGT, compute decision information, and present decision-aid options upon request. Operational requirements and restraints also were used to develop the required subsystem components that allow the primary mission to be met. Table 5 expands the integrated system architecture subsystems into their components.

Table 5. EHM Architecture Subsystems

SUBSYSTEM	COMPONENT/REQUIREMENT
Temperature Sensing	Black Globe - Globe - Sensors - Isolation of sensor/globe Dry Bulb - Shield - Sensor Wet Bulb - Sensor - Wick - Interface of wick/sensor - Water Reservoir
Data Acquisition	Wire Harness Signal Conditioners A/D Converters Data Storage

SUBSYSTEM	COMPONENT/REQUIREMENT
Computational/Modeling	ROM for S/W Software - Signa-to-Temperature Conversion - Calculation of WBGT - Calculation of Work/Rest Ratio - Calculation of Max. Work Load - Calculation of Water Consumption
System Controller	Built-In-Test (BIT) Input (Keypad) - On/Off - Desired Output - Model Parameters * Clothing * Work Load Profile * Acclimation Input (Comm. Port) [Optional] Output (Display) - Computational - BIT - Low Battery Output (Comm Port) [Optional] Sequence DAS Power
System Packaging	Case Transport Container NBC-Contamination Survivability Environmental Hardness

5.2 Potential Component Configurations

5.2.1 Temperature Sensor Components

5.2.1.1 Black Globe Temperature Sensor

To effectively measure the incoming solar and thermal radiant energy components (direct, diffuse, and reflected) the black globe temperature sensor must be omni-directional to sense direct radiant energy from any angle of incidence and should be able to sense other radiant energy (e.g., "scatter sky" solar radiation). Some "comfort meters" use oblong globe thermometers as they may be more representative of the radiation load received by a standing individual (but these have an uncertainty as to how well the individual is represented, and, this may complicate the interpretation of the actual measurements). For the purposes of this feasibility investigation, a sphere was used since it is "omni-directional" with respect to all sources of incoming thermal and solar radiation. The sphere works with direct solar

radiation because the cross-sectional area normal to the solar beam is constant regardless of the solar angle. Diffuse solar (sky), reflected solar (terrestrial or terrain), sky thermal or IR, and ground thermal are all treated as if the sources are isotropic. Globe thermometer configurations other than spherical may be explored during Phase II development, if this seems appropriate.

The requirement for the environmental health monitor-temperature suite to be a miniature, hand-held device does not allow the standard Vernon 6-inch (15-cm) black globe temperature sensor to be used.

This SBIR Phase I effort has determined that two viable black globe temperature sensor methodologies exist: (1) Analog (scaled-down Vernon globe), and (2) digital (digitally integrated matrix of surface sensors). Both of these techniques can be fielded into a hand-held device that can be used as a decision aid for the Army.

Analog Integrated Sensor

The analog, integrated-temperature black globe sensor is a scaled-down version of the standard 6-inch (15-cm) Vernon black globe sensor. The miniature Vernon black globe can have a diameter in the range of 1.5 to 2.25 inches (3.7 to 5.7cm). The temperature value of the scaled Vernon black globe has been shown to correlate with the standard 6-inch globe. The error introduced because of the scaling does not have a significant effect on the accuracy of the calculated WBGT value.

The response time of the analog integrated black globe sensor is faster than the standard Vernon globe.

The advantage of this approach is that off-the-shelf black globe sensors exist in the commercial sector. These sensors would have to be hardened to withstand the harsh treatment of the battlefield. The disadvantage of this approach is that the space within the globe must be sealed (via gaskets, not vacuum sealing) and does not allow for the most compact integrated design of an environmental health monitor. For a military device, a faster response time would also be desirable.

Digital Integrated Sensor

The digitally integrated, black globe sensor consists of an array of thermal sensors that are equally spaced on a spherical matrix. The array of thermal sensors are then integrated digitally using embedded software located on the internal CPU.

The response time of the digitally integrated black globe sensor, which has the potential for a time constant of approximately one (1) minute, as illustrated earlier in this report, can be faster than either the standard Vernon globe or the analog integrated sensor. This time constant can be reduced further by proper isolation or thermal compensation of the thermal sensor from the surrounding support matrix material.

The advantage of this approach is that it is very suitable for physical integration into a miniaturized unit with the other thermal sensors (wet- and dry-bulb) to create a hand-held environmental health monitor. The decreased time response also makes this a valid approach. The potential disadvantage of this approach is the increased electronic complexity introduced by the requirement for multiple sensors.

Both of these techniques for measuring the black globe temperature have been determined to be candidate sensor methodologies for Phase II development of a military prototype environmental health monitor-temperature suite.

5.2.1.2 Dry-Bulb Temperature Sensor

The primary function of the dry-bulb temperature sensor is to measure the temperature of the ambient air environment independent of any radiant energy source. This function requires that the dry bulb must have a thermal shield around it that will not allow any direct or diffuse radiant energy impact on the sensor element.

The radiant shield must be configured such that it does not inhibit free and rapid exchange of the air volume near the thermal sensor's active element. The free and rapid exchange of the air within the shield next to the sensing element is required such that an accurate temperature measurement of the ambient air can be obtained. The shield must also be constructed such that it will not desorb direct solar, diffuse and reflected solar, and thermal radiation from the heated ground and thereby influence the dry-bulb reading.

These conditions can be met by coating the radiant thermal shield with a highly reflective surface to reflect as much energy as possible, and by constructing the shield such that it will allow for free air flow around the sensor. Figure 5-1 illustrates some potential shielding configurations.

5.2.1.3 Natural Wet-Bulb Temperature Sensor

A conventional wet-bulb measurement can be accomplished either by using a moist temperature sensor to determine the temperature depression caused

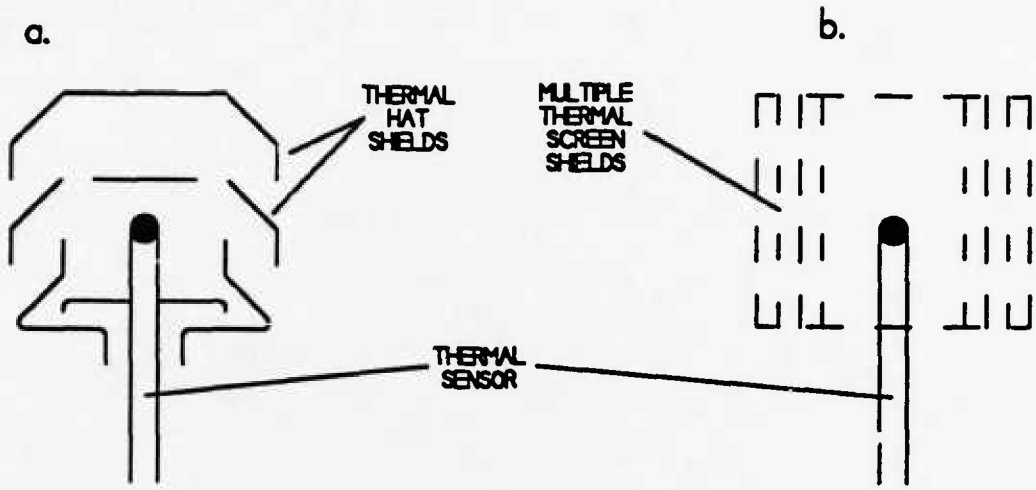


Figure 5-1. Dry Bulb Shielding Configurations

by the maximum amount of cooling from aspiration, or by measuring the dew point temperature with an electronic or optical system. These methods (as noted earlier in this report) will give the relative humidity of the environmental air mass. However, the WBGT equation uses the natural wet bulb, which is aspirated by the natural environmental air flow instead of by the aspirated air. Thus, the natural wet bulb sensor must be exposed to the ambient environment such that it evaluates the evaporation effect from radiant energy input and air flow caused by the wind. The configuration of the natural wet bulb sensor consists of a temperature sensor to determine the temperature of a moist wick material.

The observed temperature of the natural wet bulb can be influenced by either the wet-bulb hardware or by the water-reservoir temperature. The water used to maintain a moist wick is stored in a reservoir within the instrument package. Thus, the temperature of the water will generally be different from that of the environment depending upon the storage environment of the environmental health monitor before use. As the water travels up the wick material towards the location of the thermal sensor, there must be sufficient residual time allowed for the water on the wick to come to equilibrium with the wick environment as modified by the air flow. If sufficient

equilibration time is not permitted, then the temperature recorded will be a function of the natural wet bulb temperature and that of the water reservoir.

In a similar fashion, the wet bulb support hardware must be sufficiently thermally isolated from the moist wick material and the thermal sensor such that the support hardware does not act as a radiant energy input to either the wick or the temperature probe.

These sources may cause an observed temperature error cf several degrees centigrade. This error can be corrected by providing a sufficiently large wick area to permit the bulk of the water to come to equilibrium as it travels to the sensor, or by waiting a very long time for the system to come into thermal equilibrium before taking the thermal measurement.

The operational requirement that the environmental health monitor be functionally independent of its physical orientation requires that the wet bulb wick be exposed to the natural air flow (wind) independent of the wind direction. This requires 360-degree access to the wet bulb wick material to allow for wind-driven evaporation. Figure 5-2 illustrates a potential configuration for the natural wet bulb.

5.2.2 Data Acquisition/Embedded Microprocessor

The data acquisition system (DAS) configuration will take the electrical signal from the thermal sensors and store it as temperature data in RAM memory. This data acquisition process consists of thermal sensor signal conditioning, A/D conversion, and storage in memory. The DAS will operate in a multiplex mode to maximize efficiency and miniaturization of the electronic components of the environmental health monitor. The complexity of the DAS, including the selection of components and microprocessor, will depend upon the final temperature sensor configuration for the black globe thermometer; the analog black globe approach requires one thermal sensor and the digital approach requires approximately 24 thermal sensors.

The microprocessor will use available off-the-shelf military hardware. The ROM and RAM capacity will be determined by the input and output requirements of the environmental health monitor and the complexity of the decision aid model to generate the desired output. Excess processing capacity will be built into the system for future modifications.

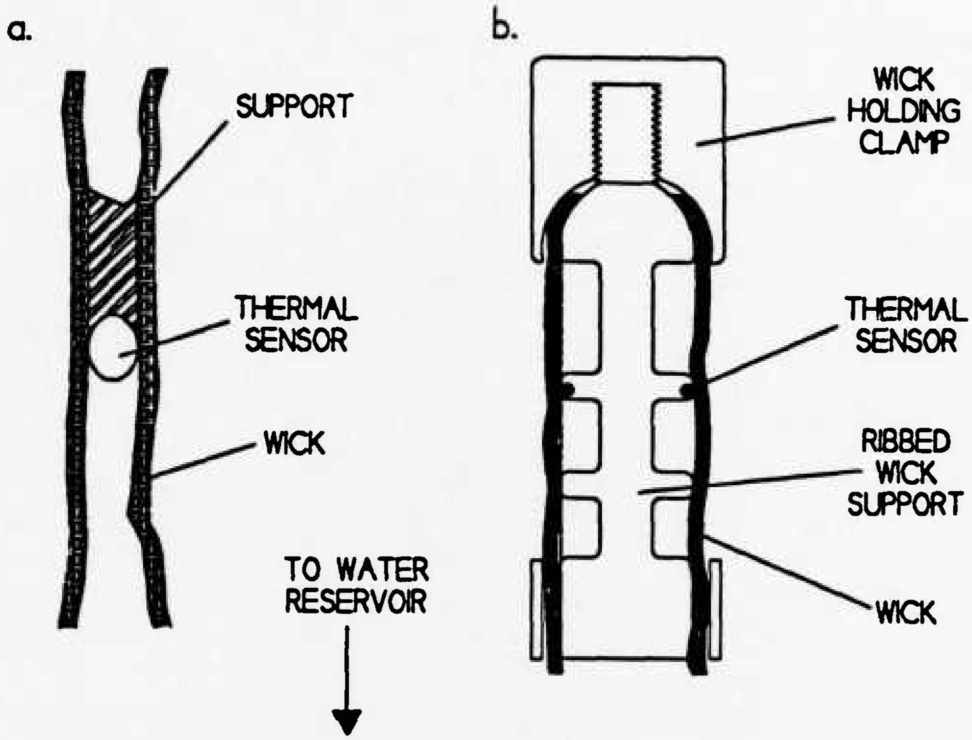


Figure 5-2. Wet Bulb Configuration

5.2.3 Input/Output Considerations

The input/output requirements for the environmental health monitor are based on the embedded computational mathematical model and the operational decision-aid requirements. Calculation of the WBGT will indicate an environmental temperature value; for example, the model must integrate this value with the status of the soldier's clothing, acclimation, and work load to generate a decision aid that will address (1) the work/rest cycle, (2) the maximum sustained work time for a given amount of heat-related casualties, and (3) water consumption in canteens per hour necessary to mitigate any dehydration.

The input to operate the temperature acquisition component of the environmental health monitor will consist at the minimum of an "ON/OFF" switch and a "BIT" (Built-In-Test) switch. These inputs are necessary to tell the system controller to take environmental temperature data, to display the WBGT temperature data, and to

perform a system self-check to determine if all systems are operational. These are the minimal operational requirements to generate WBGT environmental data and ensure system function.

The input/output requirements for this basic level would be a three-way switch and a single-line display. A BIT warning light could be included or an additional message on the one-line display.

To use the environmental data in the generation of useful decision-aid information, soldier status must also be input for use by the algorithm. The soldier status information may contain, but not be limited to, the following:

Projected Activity Profile
Projected Clothing Profile
Size and Weight of Soldier
Acclimation Characteristics

This information can be placed in the embedded memory either on an individual basis or as a weighted average of the military unit (i.e., patrol, platoon, or company).

The information needed in support of decision-aid modeling requires a keypad data entry system. The system controller can monitor the data entry by generating cues on the display window that will indicate to the soldier what information needs to be entered and what data has already been input. Thus, a two-line display could ask for a given input on line one and then shadow the input on line two to confirm that the correct data has been entered.

The output of the Environmental Health Monitor will be based upon the amount of data or decision-aid information required. Thus, the embedded algorithm can either project when individual soldiers are going to become heat-strain medical casualties as a result of their work load, clothing, and physical characteristics or it can project the degradation level of an entire unit. The water consumption necessary for both individuals and the entire military unit can also be projected for different military missions.

The input/output component of the environmental health monitor is envisioned to be an NBC-contamination-resistant, membrane keypad with a multi-line liquid crystal display that is protected with a clear NBC-contamination-resistant protective film.

As an option, a communication port could be added to the environmental health monitor. This would allow it to be accessed remotely via either a hardwire or radio

link. It may be operationally desirable to have an environmental health monitor mounted outside a collective shelter or collective protected vehicle. Thus, personnel could either continuously or periodically monitor the outside environment to determine the potential of heat-related medical casualties and water consumptions requirements for crews working in the location. It may also be desirable to have an environmental health monitor located within a vehicle such as a tank or APC to monitor the interior environmental effects upon the status of the personnel inside (and projecting both heat-strain medical casualties and water consumption requirements). The environmental health monitor could also be located with each radio operator. This would allow headquarters to automatically receive (upon demand), environmental data, and would give them the ability to plot across the battlefield environment. This information could also be used by headquarters as a planning aid to determine the current heat-stress status of the troops and the water needed to maintain a military operation.

5.2.4 Packaging

To be "mission-transparent," the environmental health monitor must be packaged as a small, effective, hand-held, fieldable instrument. This places several restraints on the internal configuration and external packaging of components. The main body of the integrated monitor must have internal volume allocated to the housing of the data acquisition system, computer chips, power supply (battery), and water reservoir for the natural wet bulb measurement. Attached to the main monitor body will be the three temperature sensors; there will be attached in a manner that ensures non-interference and provides full access to the environmental elements of direct and diffuse radiation, ambient temperature, and air flow.

The integrated packaging concept is based on the desire to have the environmental health monitor be as compact as possible in its storage/transportation and operational modes. To accomplish this objective, the monitor will fold or collapse as much as possible to generate a minimum storage/transportation profile. This has the advantage that the EHM in its storage/transportation configuration will also protect the temperature sensors (ambient and natural wet bulb) from physical harm during handling. The additional advantage of a collapsible temperature suite is that the wick of the natural wet bulb can be sealed off from the environment, conserving the limited amount of water for the wet bulb water reservoir to be used only during measurements.

The environmental health monitor packaging must be survivable against the physical abuses of the conventional battlefield as well as against the hazards of the NBC-contaminated battlefield. Both the internal arrangement of components and the physical case must be configured to withstand being dropped or mishandled during

training exercises or during mission performance under hostile conditions. In addition, the outside case and the temperature sensors must be designed to withstand the special dangers of the NBC-contaminated battlefield (i.e., to prevent liquid droplets, particles of nuclear fallout, chemical or biological agents from being trapped). The materials selected for the case and exposed surfaces of the temperature sensors must be resistant to chemical agents (to prevent off-gassing and secondary physical contamination of our troops) as well as resistant to the harsh chemical treatment of our current and future decontamination procedures and materials. Modular construction of the sensors or sensor components will be considered—especially in order to replace non-decontaminable components such as wet bulb wicks.

5.3 Potential Integrated System Configurations

The integration of the three temperature sensors (dry bulb, natural wet bulb, and the black globe) into a hand-held device consists of combining the elements of the environmental health monitor (i.e., sensor probes; input keypad; output display; main case containing the electronics; water reservoir; and power supply).

Candidate integrated concepts were developed and evaluated with respect to their abilities to obtain the desired environmental temperatures, to be packaged into a hand-held unit, to be hardened to survive the NBC-contaminated battlefield, and to be cost effective to manufacture in large quantities.

The primary evaluation factor was the ability of the potential configuration to allow the appropriate temperature values to be determined such that the WBGT value could be determined with sufficient accuracy that it would be meaningful in the battlefield.

The second evaluation factor was the ability of the potential configuration to be designed (packaged) small enough to encourage the soldier to use the equipment in the field. Operationally, the soldier is concerned about performing his or her mission and surviving. This requires that any additional equipment must be compact and light in weight to minimize additional burden. If there is space available, the soldier would prefer to carry ammunition rather than another piece of equipment.

The third evaluation factor was the ability of the potential configuration to be fabricated to withstand harsh treatment in the integrated battlefield. This evaluation was concerned with the misuse and harsh handling that equipment receives in the battlefield. The equipment is of no value to the troops if it does not have a very high mean time between failure (MTBF) rate. We were also concerned about NBC-CS (nuclear, biological, and chemical contamination survivable). The physical packaging of the equipment must be selected from materials that are not susceptible to the harsh

treatment of decontamination or to off-gassing of absorbed chemical warfare agents (generating a secondary chemical threat).

Three classes of integrated system configurations were developed as potential designs for integrating the three temperature probes into a single hand-held environmental health monitor/temperature suite. These three classes are defined as (1) Folding Probes, (2) Integrated Cage, and (3) Pop-up Configuration.

5.3.1 Folding Probe Configuration

The Folding Probe concept consists of a miniaturized globe thermal probe together with a dry bulb and a natural wet bulb that are located on arms that "fold out" from the main body of the equipment when measurements are taken—ensuring noninterference with the temperature measurement of the globe. When this configuration is placed in a storage or transportation mode, the arms would be folded back together, forming a small, compact unit. Two different configurations of this concept were evaluated.

Folding Configuration I: Solid Globe

In this concept, the folding temperature probes are hinged to the side of the main body. Figure 5-3a shows one possible configuration of this concept using rectangular fold and arms, but the shape of these arms may be altered appropriately to reduce wind or radiation-related effects on the accuracy of temperature measurements. During storage, transportation or non-use, the folding arms would be in the down position next to the main case of the environmental health monitor. When the unit is to be operated, the arms would be rotated away from the main case position and the temperature probes would then be positioned not to interfere with the radiant measurement on the globe sensor. The folding-probe EHM would either be held in the hand or would be placed on a surface with the globe oriented towards the sky.

The input/output components would be placed on the flat surface of the main body of the EHM, which houses the electronics (DAS, microprocessor, and power supply) and the water reservoir.

As it is similar in design to existing environmental health monitors—but has the distinct advantages of being smaller, lighter, and less cumbersome—this basic concept has been shown to be valid. Additional developmental challenges include hardening the extending probe arms to withstand the hostile battlefield environment and achieving sufficient rigidity to preclude the arms from bending and breaking without adding weight.

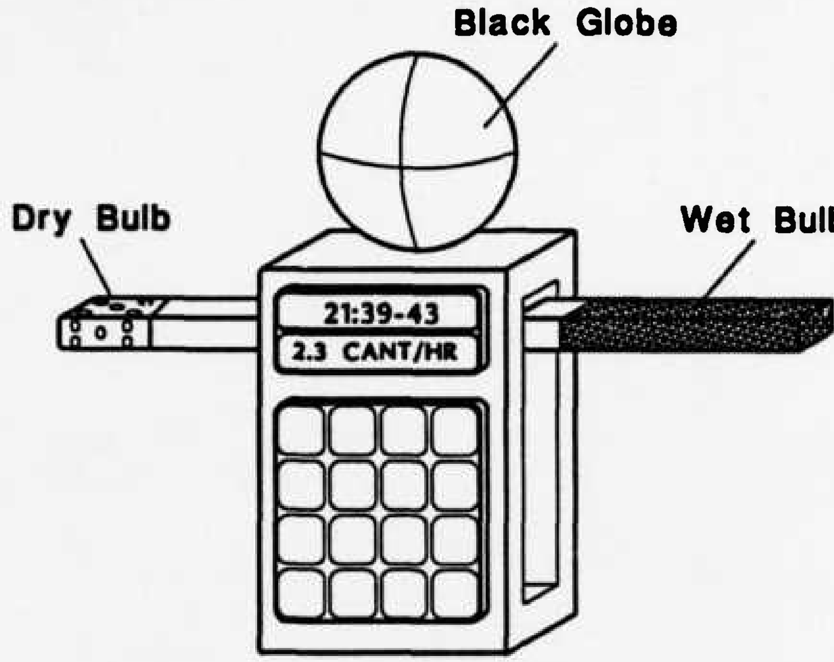


Figure 5-3a. Configuration I: Globe

Folding Configuration II: Split Globe

This is a variation on the above concept in which the globe is split into two hemispheres located at each end of the main body of the environmental health monitor with the dry and wet bulb temperature probes folded on top (Figure 5-3b). In this concept, the soldier would grasp the unit, with his or her hand around its middle, exposing each half of the globe probe to the environment. In this fashion, the globe will always be able to measure the total radiant energy input independent of the position in which it is held. The dry bulb and wet bulb temperature probes would then extend out like a TV antenna. To operate in this fashion the split globe must be a digital black globe type unit with individual thermal sensors mounted on the surface of each hemisphere.

To minimize the cross-sectional area of the main body of the environmental health monitor, the front panel area could contain the keypad for data entry and the back panel could contain the multi-line liquid crystal display unit, or both could be located on the same side (as shown) for greater convenience.

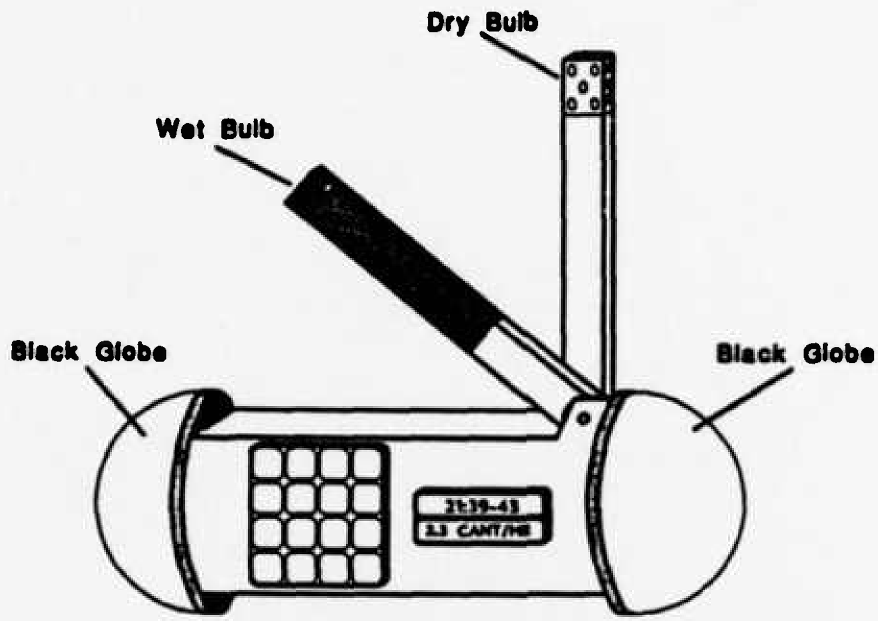


Figure 5-3b. Configuration II: Split Globe

This concept allows the globe sensor to detect radiant input at all angles, but does not permit an air flow to be maintained around the spherical globe in the same fashion as does the black globe thermometer. The practicality of using the split-globe arrangement must be further investigated.

5.3.2 Integrated Cage

The integrated cage configuration is based upon the concept that the surface-mounted temperature sensors measure the incoming radiant energy and that they only need to be supported. The resultant black globe temperature value is then the integration of the incoming radiant energy, which can be accomplished digitally. Thus, the radiant energy input can be measured by placing the surface-mounted temperature sensors on a spherical cage-like structure. With an open spherical cage structure, the dry bulb and the natural wet bulb temperature probes can be incorporated within. Figure 5-4 illustrates this concept.

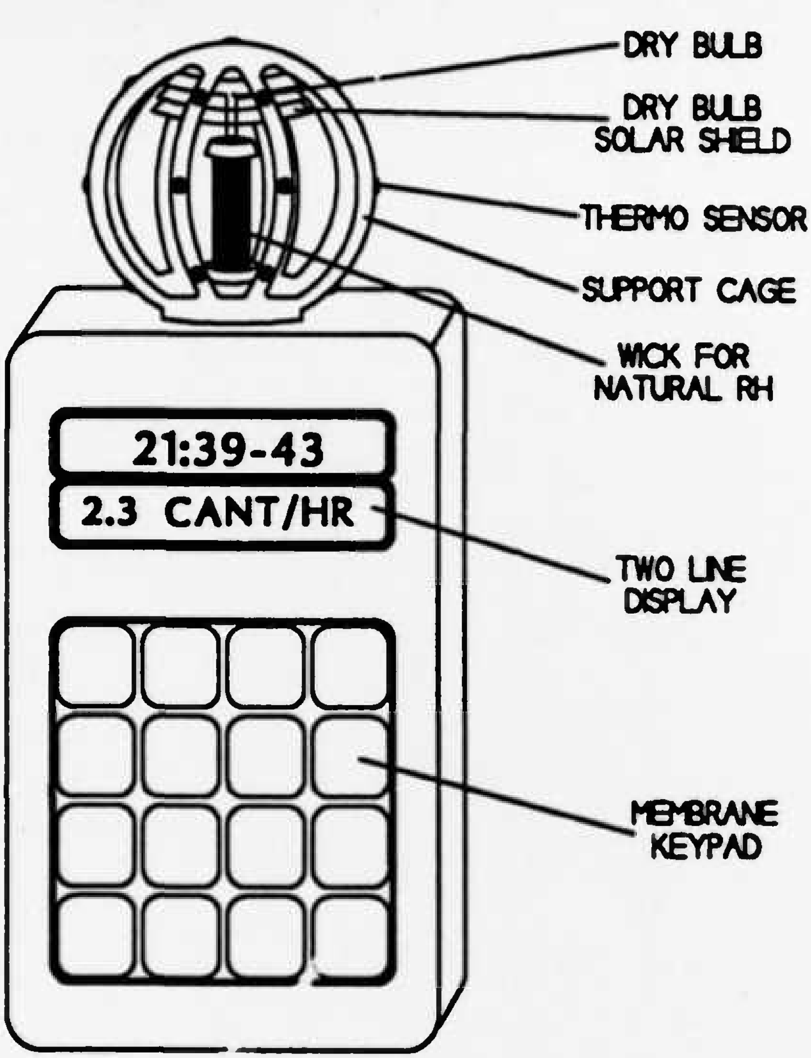


Figure 5-4. Cage Configuration (Full Size)

5.3.3 Pop-up Configuration

The Pop-up Sphere configuration is based on the concept that the interior of the radiant temperature globe can be used to store the other probes when the EHM is not being used. This would generate a more field-hardened and compact piece of instrumentation. Two different Pop-up configurations have been developed.

Pop-up Configuration I: Globe

Pop-up Configuration I features a wet bulb attached in a stationary fashion to a water reservoir located inside the main instrument package. When the EHM is to be used, the soldier would slide the globe up in an extended position, exposing the wet bulb to the natural environment. The length of the wet bulb would be approximately two inches of exposed wick. The dry bulb would be attached to the top of the globe. It would be small such that it can be effectively shielded from radiant energy, and minimize its ability to shadow a radiant globe surface temperature sensor. Figure 5-5 illustrates this concept. This configuration requires that there be a movable wire harness that contains approximately 50 leads for the surface-mounted temperature sensors and for the dry bulb.

Pop-up Configuration II: Wet/Dry Probe

The second Pop-up Probe configuration is also based on the concept that the interior of the radiant temperature globe can be used for storage of the wet/dry temperature probes. This configuration (illustrated in Figure 5-6) features a stationary globe attached to the main EHM package with a support mechanism that would be extended from the top of the globe. The support mechanism would contain the wet bulb with the dry bulb shield and sensor at the top.

This configuration allows the wet bulb to be totally exposed to the natural wind conditions without any shielding from the EHM components. This is important since 70% of the WBGT value results from the wet bulb temperature.

This configuration can generate the situation that one or at most two surface temperature sensors could be shielded from the direct radiant energy. To take this condition into account, a software temperature monitoring program could determine if a sensor is shielded (it would have a low value and be close to the dry bulb temperature reading); the program would delete readings from the shielded sensor(s) from its digital integration when calculating the "black-globe-temperature" value. If the shadow effect were ignored, the effect would be to introduce an error in the "Black Globe Temperature" of 4%. This would translate into an error in the WBGT value of 0.8% since the Black Globe temperature value is weighted by a factor of 0.2.

The dry bulb subsystem (shield and sensor) would be located at the top of the extending mechanism. In this fashion, the dry bulb would have access to the natural environment and be in a position that would not interfere with either of the other environmental temperature measurements.

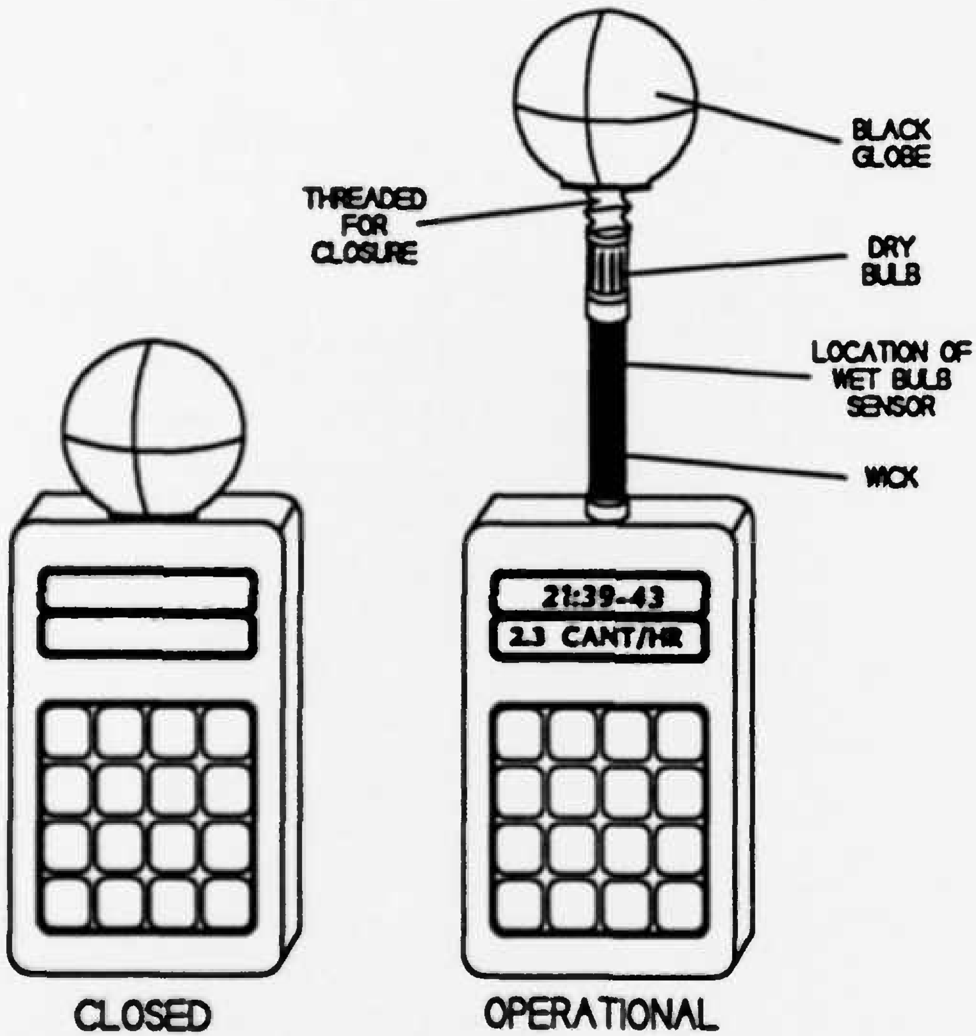


Figure 5-5. Globe Pop-Up Configuration

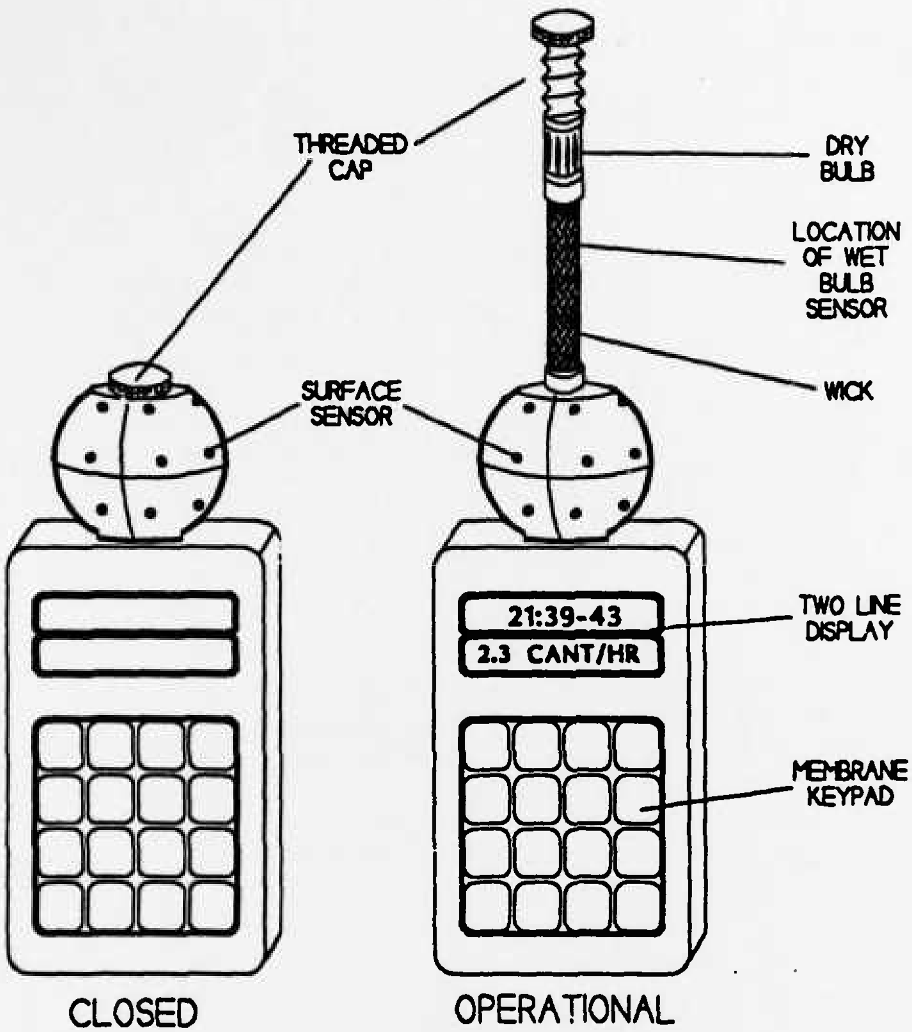


Figure 5-6. Wet-Dry Bulb Pop-Up Configuration

Section 6
RECOMMENDATIONS AND CONCLUSIONS

6.1 PHASE I Program Conclusions

The following conclusions were derived from this successful Phase I SBIR program:

1. Literature/Product Survey of Off-The-Shelf Instrumentation

   The survey of off-the-shelf commercially available sensors indicated that several environmental health monitors exist that will calculate the WBGT heat-stress value. None of these units, however are small hand-held units that are applicable for use in the battlefield, by the troops. The black globe sensor developed and patented by IST is small enough to be considered as a suitably sized globe sensor probe for an integrated Environmental Health Monitor-Temperature Suite.

2. Viability of the Digitally Integrated Surface-Mounted Temperature Sensors as a Potential Replacement for the Standard Black Globe Temperature Sensor

   The experimental work performed under this Phase I SBIR program demonstrated that the use of a matrix of individual temperature sensors mounted in a spherical array with digital integration is a valid and viable concept for the measurement of the black globe temperature component within the WBGT calculation. This concept allows the use of a smaller globe and permits the interior of the globe to be used for other purposes that will lead to further miniaturization.

   The positive results of this Phase I program indicated that the digital globe thermometer is a valid technique. However, before this methodology can be used in the development of prototype fieldable instrumentation, several technical issues must be addressed in the early part of the Phase II SBIR program. Some of these issues include the following:

   - Mounting of the temperature sensor onto the supporting matrix;

   - Isolating the sensor thermally from the supporting matrix;

- Establishing the desired time constant for the temperature sensor; and

- Developing an algorithm for the reliable prediction of equilibrium temperature based upon the temperature-time response curve.

The preliminary analysis indicates that the response curve of the temperature sensing devices, mainly in the digital globe temperature sensor, take a recognizable mathematical form. It will be possible to use this information to minimize the amount of time that the integrated environmental health monitor will require to obtain the black-globe-temperature component of the WBFT. It should be possible to reduce the time for temperature determination significantly.

3. Time-Average Natural Wet Bulb Measurement

A technical conclusion of this effort is that the dry bulb and the digital integrated globe temperature values can be determined in minutes. However, the natural wet bulb temperature value is affected by the variations in the air flow across the wick. At lower wind speeds, the fluctuations of the wind can be as great as 100%. Thus, it will be necessary to integrate the wet bulb measured value over a sufficient time period that the resultant temperature value is representative of the natural environment. It is recommended on the basis of discussions with manufacturers of commercial wet bulb systems and in recognition of the fact that both the wind speed and direction naturally vary over a period of a few minutes that an integrated wet bulb reading of five minutes be used to ensure the accuracy of the calculated WBGT value.

6.2 Recommended Integrated Configurations

6.2.1 Temperature Sensor Suite

There are three potential temperature suite configurations that should be considered for evaluation in a Phase II SBIR program. Each of these candidate configurations (Figure 6-1) has the potential of leading to a small, compact hand-held environmental health monitoring device.

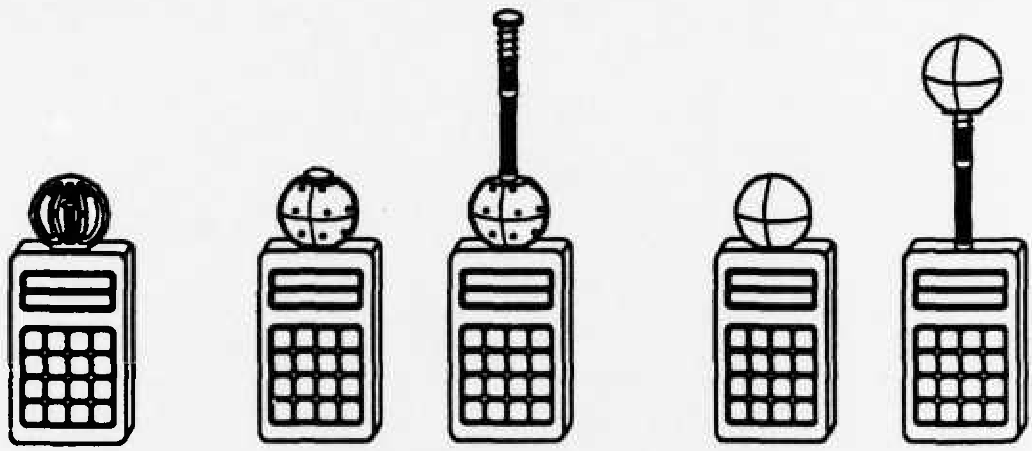


Figure 6-1. Three Recommended Integrated Configurations in an Open and Closed Position

The Cage Configuration allows for a field-hardened metal or plastic spherical cage to be the supporting matrix for the surface-mounted radiant temperature sensors, which will be digitally integrated to generate the globe temperature component of the WBGT calculation. The dry bulb and the wet bulb can be located within the interior of the cage. This serves the purpose of protecting the dry bulb and the wet bulb from rough handling and allows for a compact temperature suite. The potential disadvantage of the use of a cage for the globe temperature is that the effect of air turbulence on cooling a solid globe would be eliminated. The error that this introduces into the WBGT calculation should be within acceptable limits. The dry bulb would be located at the top of the cage configuration atop the wet bulb. In this fashion, it can be properly shielded from direct and diffuse radiant thermal sources and generate an accurate ambient dry bulb reading. The wet bulb would be located in the center of the cage with the wick going directly into a water reservoir located in the main body of the environmental health monitor.

There are two pop-up configurations. The first configuration features a globe attached directly to the main body of the environmental health monitor. The wet and dry bulb pop out of the center of the globe when a temperature reading is required and recess back into the globe when the environmental health monitor is not being used.

This configuration has the advantages of protecting the wet bulb wicking mechanism and conserving water from evaporating from the water reservoir. Having the digital globe connected directly to the main body of the environmental health monitor allows for direct electrical connection of the 24 thermal sensors, which increases reliability.

The second pop-up configuration has a solid miniature black globe attached to the top of a dry/wet bulb support unit. The miniature black globe pops up from the environmental health monitor to expose the dry and wet bulb to the environment when taking a measurement. This configuration also protects the wet and dry bulb from physical harm and minimizes water evaporation when the equipment is not in use. The use of a miniature black globe also requires only one thermistor, instead of 24 for the required measurement. The disadvantage of this configuration is the increased time for the miniature globe to achieve thermal equilibrium after an incremental change of temperature.

Figure 6-1 illustrates the three configurations presently recommended for Phase II evaluation and downselect for subsequent development. Each configuration is suitable for design integration of field hardening and NBC contamination/survivability modifications.

6.2.2 Electronic Support Package

It is recommended that the electronic support package contain an embedded CPU with sufficient memory to store the incoming temperature data as well as the operator input that will be required for the calculation of decision aids.

The data acquisition subsystem will consist of sensor signal conditioners and a sensor monitoring system that will index the incoming temperature data to the correct memory location.

The embedded CPU will also contain ROM-embedded software that will automatically calculate the WBGT value based upon the dry, natural wet, and black globe temperature readings. The embedded software will also take operator input with the calculated WBGT values and determine information that can be used as a

decision aid. This will allow improved management of behavioral responses to the environmental conditions contributing to heat stress.

It is envisioned that a membrane keypad will be incorporated into the environmental health monitor to allow the operator to turn the equipment on and off and obtain BIT information. The keypad can also be used to enter non-temperature model information, which will be required to determine the proper decision-aid options. A multi-line alphanumeric display unit will enable the transfer of the greatest information to the operator and ensure that manual data is properly entered into storage.

6.2.3 Package

It is envisioned that the environmental health monitor will be packaged in a modular format to reduce life cycle costs and to prevent the water in the wet bulb water reservoir from entering into the electronic compartment. The four basic modules will be

- Integrated/Sensor suite (wet, dry, globe);
- Water reservoir;
- Electronic support package; and
- Power supply.

A transportation case will either be developed as a integral part of the environmental health monitor or it will be a separate item that will also carry auxiliary equipment that the Army may wish to transport. The auxiliary equipment may consist of a monopod/tripod to keep the EHM four feet off the ground during environmental measurements, mounting brackets that will allow the EHM to be mounted on a vehicle or a shelter, and water demineralizer to maintain clean water for the wet bulb.

6.3 Applications of the Compact Hand-Held Environmental Health Monitor

6.3.1 Military

There are two distinct military uses for a miniaturized hand-held environmental health monitor: (1) To prevent or reduce medical casualties resulting from heat strain during combat missions; and (2) To improve soldier safety during field training exercises.

Such a device should be as transparent to the normal military operation as possible. It can be used either by an individual soldier during special missions (such as "behind-the-enemy-lines" operations performed by the Special Operation Forces), or by a group of soldiers in a platoon or company. The availability of the type of information the EHM could provide would also lead to improved mission planning that incorporated environmental heat-stress factors.

The miniaturized environmental health monitor can be either hand-held and carried by a soldier or it can be mounted to a vehicle or shelter for monitoring the environment.

The miniaturized compact environmental health monitor could also be used to decrease the risk of heat-related medical casualties during training at the National Training Centers, full-scale field exercises in CONUS or other operational theaters, and at basic or advanced training camps and reserve centers.

6.3.2 Civilian

People in various states of physical condition regularly attempt physical exercise or strenuous tasks. Since a heat-strain medical casualty can occur virtually without warning,[24] an inexpensive environmental health monitor could be a valuable aid in preventing work or leisure-activity-related heat strain in the civilian sector as well.

Many persons also now work in civilian jobs that require protective clothing (e.g., firefighters, forestry service personnel, field workers in the construction and agricultural industries, production workers in facilities where hazardous chemicals may be present, etc.). The environmental conditions that these people work under need to be monitored so that they are given the proper work/rest ratio, and liquid intake to eliminate heat-stress-related injuries. Doing so could lead to reductions in workers compensation insurance costs.

6.4 Phase II Recommendation

It is our recommendation that a Phase II SBIR program be pursued to develop, test, and deliver to the US Army Institute of Environmental Medicine a compact hand-held Environmental Health Monitor-Temperature Suite.

It is recommended that this be a two-year program that will perform the following tasks:

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[24] For example, a person may be significantly dehydrated prior to having a thirst sensation.

- Evaluate the proposed candidate temperature suite configurations based upon technical and cost to manufacture considerations;
- Develop a brassboard EHM that can be used to validate the subsystem and component design elements;
- Fabricate and validate the technical capability of a prototype EHM; and
- Deliver a prototype to the USARIEM together with a comprehensive final report.

It is also recommended that a feasibility study to develop other environmental sensors such as an aspirated wet bulb and a wind speed indicator be conducted. The goal of this feasibility study would be to determine the viability of generating an Environmental Health Monitor-Temperature Suite that would use a heat stress model developed by USARIEM.

SUPPLEMENTARY

INFORMATION

DEPARTMENT OF THE ARMY
U.S. ARMY MEDICAL RESEARCH, DEVELOPMENT, ACQUISITION, AND LOGISTICS COMMAND (PROVISIONAL)
FORT DETRICK, MARYLAND 21702-5012

REPLY TO
ATTENTION OF

ERRATA

SGRD-RMI-S (70-1y)

25 AUG 1994

MEMORANDUM FOR Administrator, Defense Technical Information Center, ATTN: DTIC-HDS/William Bush, Cameron Station, Bldg. 5, Alexandria, VA 22304-6145

SUBJECT: Request Change in Distribution Statements

1. The U.S. Army Medical Research, Development, Acquisition, and Logistics (USAMRDAL) Command (Provisional), has reexamined the need for the limited distribution statement on technical reports in the Defense Technical Information Center database. Request the limited distribution statement for [redacted], [redacted], and ADB173851, be changed to "Approved for public release; distribution unlimited," and that copies of these reports be released to the National Technical Information Service.

2. The point of contact for this request is Ms. Virginia Miller, DSN 343-7328.

Carey O. Leverett

CAREY O. LEVERETT
LTC, MS
Deputy Chief of Staff for
Information Management

151.20/14

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AD-B173 851